SECTION 6—DIRECTED ENERGY (DE) AND KINETIC ENERGY (KE) SYSTEMS TECHNOLOGY

Scope

Highlights

- Particles from beam weapons travel to the target at a velocity close to the speed of light.
- Beam weapons, depending on the type of particle and energy, use a range of lethal mechanisms. This results in a variety of effects—from soft kill to hard kill.
- Development of a successful charged particle beam (CPB), neutral particle beam (NPB), and antimatter particle beam (APB) weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures.
- NPBs can be used in space applications as antimissile and antisatellite weapons.
- APBs provide high-energy deposition even at low accelerator power [low kinetic energy (KE)].
- A gamma-ray laser beam (graser) will penetrate deep into a target, unlike visible and infrared (IR) laser beams, and will be capable of producing a range of lethal mechanism—from soft kill to hard kill.
- A gamma-ray laser weapon is nominally considered for space application—to be used against missiles and satellites.
- Because the gamma-ray laser beam, when developed, will travel at the speed of light, tracking problems associated with slower beams [particle beams (PBs)] will be avoided.
- The deeper penetration of the high-energy photons in a target overcomes the countermeasures designed against beams that deposit energy on the surface (e.g., long-wavelength lasers).
- For KE weapons, massive kill is projected since projectile produces catastrophic destruction.
- For missile deployment, kinetic energy weapons (KEWs) need to span a velocity range of 1 km/sec to 14 km/sec and weigh from 10 kg to 10,000 kg.
- For KEW systems, computer simulations are used to determine lethality in situations where tests are costly or otherwise impractical.
- Electromagnetic (EM) signals produced by high-powered microwaves (HPMs) enter military systems through unconventional and/or inadvertent pathways, causing permanent damage or temporary upset to mission-critical electronic equipment.

Highlights (Continued)

- High-power microwave/radio frequency (HPM/RF) weapons use EM waves as a directed energy (DE) beam under a variety of battlefield conditions.
- Building HPM/RF weapons requires advances in making the following components more compact and energy efficient: prime power sources, high-peak-power and/or average-power microwave sources, pulse power systems, and high-gain antennas.
- Major innovations and breakthroughs in testing and simulation will enable the military to predict successfully the susceptibility of systems against HPM/RF threats.

OVERVIEW

This section addresses directed energy (DE) and KE systems, which are advanced technologies that may completely change the way future military missions are organized and executed. Under DE systems, we include CPBs, NPBs, APBs, and HPMs. High-energy lasers (HELs) are treated in *Developing Critical Technologies, Section 11, Lasers and Optics Technology*. Under KE systems, we include electromagnetic launch (EML) systems [e.g., railguns and coilguns, electrothermal (ET) guns, and electrothermal chemical (ETC) guns].

CPBs and NPBs travel close to the speed of light and cause physical destruction to the target's surface and interior. Their lethality and depth of penetration are a function of their KE. Charge effects, such as dielectric breakdown, can also occur. APBs cause the total annihilation of particles with which they collide. Their lethality and energy deposition is nearly independent of their KE. HPMs travel at the speed of light and are designed to produce system malfunction by causing permanent damage to an electronic component or temporary upset to an electronic subsystem.

All the KEW systems generate projectiles that travel at velocities greater than 1.8 km/sec and destroy targets by severe rupture. Of the KE weapons systems listed, only the ET guns and ETC guns are sufficiently mature to have been included in a current military system. However, research laboratories have conducted a substantial amount of research and development (R&D) work on the other technologies.

We first discuss PBs. The PB weapons project atoms (neutral particles), ions, electrons, or other subatomic particles from a high-energy accelerator to a distant target. The supporting systems include technologies for high-current PB generation and acceleration; high-burst power generation; beam control and monitoring subsystems; target interaction and kill assessment; and systems analysis. In all weapons applications, lethality dictates high currents and high KEs, which translate to high-power requirements for normal PBs. For APBs, this requirement is substantially modified.

Microwave technology deals with the use of intense radio frequency (RF) waves as DE against military targets or segments of civilian systems that support military operations. This form of DE is capable of being delivered on target either as a series of pulses or as a continuous wave (CW). This section emphasizes the frequency range above 100 MHz and extending into the mid-to-high end of the microwave region. For military systems, we expect that most interest will be in the 500-MHz to 30-GHz range.

The concept of using EM energy in military combat goes back more than 60 years. Jamming and/or spoofing radar and communication receivers by overpowering them with manmade noise and other unwanted signals traditionally has been termed electronic warfare (EW). Today, this military use of RF is also called information warfare (IW).

Traditional EW techniques make no attempt to destroy physically the electronic components of radar, communication, or navigation receivers or any other RF sensor. HPM/RF DE signals, on the other hand, are intended to adversely affect systems more than typical EW signals because of their on-target higher power density and/or energy density. The goal of HPM/RF weapons is not to have a specific unwanted waveform for a specific target; rather, the goal is to have a few classes of waveforms that can attack many different systems. This is often referred to as a generic countermeasure. In addition, HPM/RF signals can disrupt the normal operation of some military information systems by mechanisms involving the insertion of incorrect information into the electronics.

SECTION 6.1—CHARGED PARTICLE BEAMS (CPBs)

> ***Highlights***
>
> - CPBs from beam weapons travel to the target at a velocity close to the speed of light.
> - CPB weapons, depending on the type of particle and energy, use a range of lethal mechanisms. This results in a variety of effects—from soft kill to hard kill.
> - Development of a successful CPB weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures.

OVERVIEW

This section addresses technology for the generation, propagation, and control of high-intensity electron beams (e.g., CPBs): high-current electron beam generation and acceleration, high-burst power generation, beam control and monitoring subsystems, target interaction and kill assessment, and systems analysis. It also addresses the question of lethality and how electron beams physically interact with matter to cause destruction.

For historical reasons, electron beam systems have received the greatest amount at attention. Lethality dictates high currents (greater than 5 kA) and high KEs (greater than 10 MeV), which translates to high peak power (greater than 50 GW) requirements.

Electron beams have high current in excess of 5 kA, KEs in excess of 10 keV for space operation and 10 MeV for surface operation on land or sea, and, consequently, high power in excess of 50 GW.

To be able to use these beams effectively as weapons:

- Accurate target detection and location are required.
- Accurate beam pointing and control have to be available. This includes beam sensing and steering dynamic alignment and target-hit detection.
- The phenomenology of beam propagation, including scattering beam pulsing effects, absorption, and the effect of instabilities, has to be understood and included in the systems analysis.
- Kill assessment is critical to effectiveness and efficiency, especially against multiple targets; therefore, the phenomenology of beam target interaction has to be understood and folded into the systems analysis.

Electron beam pointing and control subsystems include beam directors and sensing assemblies. The technology that enables practicable beam pointing systems relates to precise beam sensing and steering, dynamic alignment, reference and control, target hit detection, kill assessment, vehicle environment effects on fine pointing, and radiation effects on sensors and instruments.

CPB weapons project electrons or ions from high-energy accelerators to a distant target and potentially have endoatmospheric and exoatmospheric applications. They deliver energy at a significant fraction of the speed of light. Unlike HELs, the energy is deposited beneath the surface and over a range of the target depending on the beam energy. This adds another dimension to the kill mechanism/countermeasure considerations. After interactions with the CPBs, catastrophic kills have been predicted from only nanoseconds to seconds. Predicted results include warhead detonation and structural breakup at higher fluences and electronic upset at lower fluences. Precise beam control is required to engage distant threats, and high fluences and fast slewing of the beam are required for interaction with multiple targets.

Scattering and absorption impose limits on the distance over which CPBs can propagate through the atmosphere. Various instabilities can drastically reduce propagation distances. Instabilities can potentially be overcome by the proper choice of beam parameters. Measuring and characterizing the interaction of an energetic electron beam and matter requires sophisticated instruments and techniques. Data acquired are critical to the design and use of electron beam weapon systems.

CHARGED PARTICLE BEAM (CPB) SYSTEM REQUIREMENTS

CPBs have been proposed for military operations for which different beam characteristics and operational procedures are required. For hard kill, enough energy has to be deposited to incapacitate the target through shock or thermal effects. For discrimination (determining the true nature of a target, warhead, or decoy), the target has only to be excited to such an extent that it provides a signature revealing its true identity.

To be militarily useful, a CPB weapon system has to provide a required dose of energy on target, determine the effectiveness of the action, and, if successful, move the beam to the next target and repeat the procedure. To do this effectively, the system has to be able to track one or more targets, produce a laser beam, point this beam at the selected target, and provide enough energy on target to complete the mission.

Development of a successful CPB weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures. For convenience, we consider the CPB weapon system as being composed of five subsystem technologies:

- Beam generation and control
- Target interaction/kill assessment
- Countermeasures/systems analysis
- Target acquisition/tracking systems
- Equipment with rapid beam slew capability.

For each subsystem, we need to identify the constituent components and determine the values of the critical parameters of the relevant components.

Measuring and characterizing the interaction of an energetic CPB and matter requires sophisticated instruments and techniques. Data acquired are critical for designing and using CPB weapon systems. These data are needed to determine the most efficient kill mechanism, detect when kill has occurred, and tailor the weapon system to mission requirements.

Accurate focusing and steering of CPBs requires precise focusing magnets. Producing these large-aperture precision steering and focusing magnets requires large, high-speed computers that can perform finite analysis of magnetic fields; accurate, numerically controlled (NC) milling equipment; and the ability to mold large high-field-stress ceramic materials. The new high-temperature superconducting magnet materials offer exciting possibilities.

Various CPB concepts may require different components or components with different characteristics for beam generation and control systems. Subsystems that fulfill similar functions in the various concepts include ion sources, accelerators, injectors, magnetic transport, RF power tubes, and prime power/power conditioning.

LIST OF TECHNOLOGY DATA SHEETS
6.1. CHARGED PARTICLE BEAMS (CPBs)

DATA SHEET 6.1. CHARGED PARTICLE BEAMS (CPBs)

Developing Critical Technology Parameter	Beam generation, acceleration, and control: Electron energy > 10 MeV, pulse energy > 10 kJ, repetition rate > 100 pps Either: peak power > 50 GW or average power > 5 MW. Accelerator and current injector characteristics: Beam currents > 5 kA, repetition rate 100 pps. Magnetic induction/transport, dynamic and beam control (tuning): Amplifiers high power > 10 kW, wide band > 100 MHz. Emerging technologies to reach goals of high power, high energy, high current, and high repetition rate: Large gradient accelerators to get high energies High-current generators Hollow catheter discharge for electron beam source.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	NC machine tools; ion source preparation technology; copper brazing technology; radio frequency quadrupole (RFQ) design and operation; precision measurements.
Unique Software	Computer design and operation codes; accelerator cavity alignment inspection code; B-field mapping codes; computer codes for accelerator design; magnetic beam line design.
Major Commercial Applications	CPB fusion. Inertial fusion: Nuclear defense simulation and hardening test Welding, material forming Material processing and modification: Ion implantation Localized heating Annealing of surfaces.
Affordability	Not an issue.

SECTION 6.2—NEUTRAL PARTICLE BEAMS (NPBs)

Highlights

- NPBs from beam weapons travel to the target at a velocity close to the speed of light.
- NPBs can be used in space applications as antimissile and antisatellite weapons.
- NPB weapons, depending on the type of particle and energy, use a range of lethal mechanisms. This results in a variety of effects—from soft kill to hard kill.
- Development of a successful NPB weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures.

OVERVIEW

This section addresses technologies for the generation, propagation, and control of high-intensity atomic beams of hydrogen or its isotopes. Included are technologies that deal with high-current (tens of milliamperes) negative hydrogen ion beam generation and acceleration; beam neutralization; high burst-power generation; beam control and monitoring subsystems; target interaction and kill assessment; and systems analysis.

NPB weapons project atoms of hydrogen or its isotopes from a high-energy accelerator to a distant target (in excess of 100 km) at a significant fraction of the speed of light. NPBs potentially have only exoatmospheric applications. Our interest is in high current in excess of 50 mA, high KEs on the order of megavolts, and beam brightness above 40 A/cm^2-mrad^2.

To be able to use NPBs effectively as weapons:

- Accurate beam pointing and control have to be available. This includes beam sensing and steering dynamic alignment and target hit detection.
- Efficient neutralizing mechanisms have to be used to provide the NPB at the output from the charged beam in the accelerator.
- High-duty factors are required because military operations demand that vast amounts of power be generated in space.
- Kill assessment is critical to effectiveness and efficiency, especially against multiple targets; therefore, the phenomenology of beam-target interaction has to be understood and folded into the systems analysis.

To produce NPBs, charged ion beams are generated, accelerated, pointed, and then neutralized. Lethality dictates high current (milliamperes) and high KEs (megavolts), which translates to high power requirements. High-current NPB generators consist of an injector or ion source that produces the initial PB, a post-injection accelerator that increases the particle velocity almost to the speed of light, and devices to extract the beam. To produce a low-divergence (focused) beam for military applications, a beam brightness above 40 A/cm^2-mrad^2 and current above 50 mA are essential. [Brightness is defined as the current divided by the product of the pair of orthogonal transverse, normalized root mean square (rms) emittances.]

NEUTRAL PARTICLE BEAMS (NPB) SYSTEM REQUIREMENTS

NPBs have been proposed for military operations for which different beam characteristic and operational procedures are required. For hard kill, enough energy has to be deposited to incapacitate the target through shock or thermal effects. For discrimination (determining the true nature of a target, warhead, or decoy), the target has only to be excited to such an extent that it provides a signature revealing its true identity. With NPB, this signature could be characteristic of the nuclear species and not just a reflection of the total mass.

To be militarily useful, an NPB weapon system has to provide a required dose of energy on target, determine the effectiveness of the action, and, if successful, move the beam to the next target and repeat the procedure. To do this effectively, the system has to be able to track one or more targets, produce a laser beam, point this beam at the selected target, and provide enough energy on target to complete the mission.

Development of a successful NPB weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures. For convenience, we consider the NPB weapon system as being composed of five subsystem technologies:

- Beam generation and control
- Target interaction/kill assessment
- Countermeasures/systems analysis
- Target acquisition/tracking systems
- Equipment with rapid beam slew capability.

Various NPB concepts may require different components or components with different characteristics for beam generation and control systems. Nevertheless, some subsystems that fulfill similar functions in the various concepts include ion sources, accelerators, injectors, magnetic transport, RF power tubes, and prime power/power conditioning. For each subsystem, we need to identify the constituent components and determine the values of the critical parameters of the relevant components.

Measuring and characterizing the interaction of an energetic NPB and matter requires sophisticated instruments and techniques. The acquired data are critical for designing and using NPB weapon systems. These data are needed to determine the most efficient kill mechanism, to detect when kill has occurred, and to tailor the weapon system to mission requirements. Also, data are required on the target's characteristic emissions for discrimination.

Accurate focusing and steering of NPBs requires precise focusing magnets. Producing these large-aperture precision steering and focusing magnets requires large, high-speed computers that can perform finite analysis of magnetic fields; accurate, NC milling equipment; and the ability to mold large high-field-stress ceramic materials. New, high-temperature superconducting magnet materials offer exciting possibilities for the future.

Finally, efficient neutralizing technology is required to convert the focused low-divergence CPB (which has limited range) into a formal low-divergence NPB that can propagate much farther.

The accelerator is the heart of the NPB generator. It must accelerate the beam to maximum energy while maintaining the beam qualities that maximize target effect and allow the best atmospheric propagation (if required). Technical data regarding size, weight, acceleration gradient, power handling, beam control, and other factors are critical when means are found to exceed generally known parameters. An important figure of merit for accelerators is the accelerating gradient (i.e., the amount of KE imparted to a particle per unit accelerator length). High-current (≥ 200 mA average), low-normalized-emittance ($\leq 0.1\ \pi$ cm-mrad) ion accelerators with average acceleration gradients greater than 5 MeV/m are military significant and should be controlled.

The development of particle sources for injection into the accelerator is critical. Not only are high currents needed, but a high-quality beam is also required when quality is associated with low emittance. Low emittance (less than $0.1\ \pi$ cm-mrad for negative hydrogen ion beams) results from high-current-per-unit area and small-beam divergence.

Short-term energy-generation subsystems are essential. These subsystems provide the pulsed energy necessary to power some PB accelerators. Key elements include high-repetition-rate switches, short-term energy storage devices, pulse conditioning equipment and power transport devices, continuous power supplies, and prime power supplies. While many of these components will be drawn from well-established and widely available technologies, the design and integration techniques needed to meet the stringent performance and environmental requirements are likely to be held almost exclusively by the United States for the foreseeable future.

PB pointing and control subsystems include beam directors and sensing assemblies. Technology enabling PB pointing systems is related to precise beam sensing and steering, dynamic alignment reference and control, target hit detection, kill assessment, vehicle environment effects on fine pointing, and radiation effects on sensors and instruments.

NPBs must be charged to be accelerated, but exoatmospheric beams must be neutralized so that the repulsion of like-charged particles will not spread the beam to a noneffective power density before it reaches the target. After the beam has been accelerated, achieving a high degree of neutralization without excessively scattering the beam is very difficult. Techniques that make this possible are critical.

High-brightness NPB systems for space have weapons applications as their only utility. The subsystems have capabilities beyond the civilian needs for PB fusion, spacecraft charging experiments, auroral studies, or as space survey instruments.

The key NPB parameters that distinguish military applications from civilian applications are:

- High duty factor for military application
- Beam brightness of a weapon system
- High-precision beam control and slewing of a military system
- Thin, large-diameter foils for military systems.

LIST OF TECHNOLOGY DATA SHEETS
6.2. NEUTRAL PARTICLE BEAMS (NPBs)

DATA SHEET 6.2. NEUTRAL PARTICLE BEAMS (NPBs)

Developing Critical Technology Parameter	Beam generation, acceleration, and control: Energy > 10 MeV, current > 50 mA, brightness > 40 A/cm^2-mrad^2 Range > 100 km. Ion sources and injectors: Low emittance < 0.1π cm-mrad, high current > 50 mA. Accelerators: Current > 200 mA, electric field gradient > 5 MeV/m Beam energy > 1 MW. RF power tubes and prime power/power conditioning: Power > 100 kW peak/tube or > 1 kW CW High-power duration on the order of milliseconds to 10 sec. Beam neutralization: Diameter > 25 cm, foil thickness < 20 mg/cm^2. Magnetic transport: Precision magnetic optics. Emerging technology: RF power accelerator technology pursued to enhance beam power to 300 MW of beam power at 800 MeV.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	NC machine tools; ion source preparation technology; copper brazing technology; RFQ design and operation.
Unique Software	Computer design and operation code; magnetic beam line design; precision measurements; computer codes for simulating generators (e.g., RF).
Major Commercial Applications	Material modification; welding; material testing; Ion implantation; space propulsion; inertial confinement fusion,
Affordability	Not an issue.

SECTION 6.3—ANTIMATTER PARTICLE BEAMS (APBs)

Highlights

- APBs from beam weapons travel to the target at a fraction of the speed of light.
- APB weapons, depending on the type of particle and energy, use a range of lethal mechanisms. This results in a variety of effects—from soft kill to hard kill.
- APBs provide high-energy deposition even at low accelerator power (low KE).
- Development of a successful APB weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures.

OVERVIEW

This section addresses technologies for the generation, propagation, and control of antimatter beams of hydrogen or its isotopes. Included are technologies dealing with the preparation, storage, and transfer of antiparticles; negative antimatter hydrogen ion beam generation and acceleration; high burst power; beam control; monitoring subsystems; target interaction and kill assessment; and systems analysis.

APB weapons project antimatter atoms of hydrogen or its isotopes from a high-energy accelerator to a distant target (in excess of 100 km) at a fraction of the speed of light. APBs potentially have only exoatmospheric or space applications because the atmosphere would erode them significantly. Interaction of the APB with a target consisting of normal matter results in complete annihilation of the beam and an equal amount of normal matter in the target. We are interested putting from 0.1 to 10 µg of antimatter on target.

To be able to use these beams effectively as weapons:

- Antiparticle storage and transfer technology has to be available on a military platform.
- Antiparticle production has to increase to more than 5 mg/year.
- Accurate beam pointing and control has to be available, which includes beam sensing and steering dynamic alignment and target-hit detection.
- Efficient neutralizing mechanisms have to be used to provide the neutral APB at the output from the charged APB in the accelerator.
- High duty factors required for military operation demand that vast amounts of power be generated in space.
- Kill assessment is critical to effectiveness and efficiency, especially against multiple targets; therefore, the phenomenology of beam-target interaction has to be understood and folded into the systems analysis.

To produce APBs, charged antimatter ion beams are generated, accelerated, pointed, and then neutralized. With APBs, lethality does not dictate both high current (milliamperes) and high KEs (megavolts), as with normal matter NPBs, because energy deposition is nearly independent of KE.

ANTIMATTER PARTICLE BEAM (APB) SYSTEM REQUIREMENTS

To be useful militarily, an APB weapon system has to provide a required dose of energy on target, determine the effectiveness of the action, and, if successful, move the beam to the next target and repeat the procedure. To do this effectively, the system has to be able to track one or more targets, produce a laser beam, point this beam at the selected target, and provide enough energy on target to complete the mission.

Development of a successful APB weapon system presupposes knowledge of the beam-target interaction physics and information about viable countermeasures. For convenience, we consider the APB weapon system as being composed of six subsystem technologies:

- Beam generation and storage
- Beam control
- Target interaction/kill assessment
- Countermeasures/systems analysis
- Target acquisition/tracking systems
- Equipment with rapid beam slew capability.

Various APB concepts may require different components or components with different characteristics for beam generation and control systems. Nevertheless, some subsystems that fulfill similar functions in the various concepts include ion sources, accelerators, injectors, magnetic transport, RF power tubes, and prime power/power conditioning. For each subsystem, we need to identify the constituent components and determine the values of the critical parameters of the relevant components.

Measuring and characterizing the interaction of an energetic APB and matter requires sophisticated instruments and techniques. The acquired data are critical for designing and using APB weapon systems. These data are needed to determine the most efficient kill mechanism, to detect when kill has occurred, and to tailor the weapon system to mission requirements. Also, data are required on the target's characteristic emissions for discrimination.

Accurate focusing and steering of APBs requires extremely precise focusing magnets. The ability to produce large-aperture precision steering and focusing magnets requires large, high-speed computers that can perform finite analysis of magnetic fields; accurate, NC milling equipment; and the ability to mold large high-field-stress ceramic materials. New high-temperature superconducting magnet materials offer exciting possibilities for the future.

Finally, efficient neutralizing technology is required to convert the focused low-divergence CPB (which has limited range) into a formal low-divergence APB that can propagate much farther.

The accelerator is the heart of the APB generator. It must accelerate the beam to maximum energy while maintaining the beam qualities that maximize target effect and allow the best atmospheric propagation (if required). Technical data regarding size, weight, acceleration gradient, power handling, beam control, and other factors are critical when means are found to exceed generally known parameters.

APBs must be charged to be accelerated, but exoatmospheric beams must be neutralized so that the repulsion of like-charged particles will not spread the beam to a noneffective power density before it reaches the target. After the beam has been accelerated, achieving a high degree of neutralization without excessively scattering the beam is very difficult. Techniques that make this possible are critical.

Short-term energy-generation subsystems are essential. While many of the components will be drawn from well-established and widely available technologies, the design and integration techniques needed to meet the stringent performance and environmental requirements are likely to continue to be held almost exclusively by the United States for the foreseeable future.

The key APB parameters that distinguish military applications from civilian applications are:

- High duty factor for military application
- Beam brightness of a weapon system
- High-precision beam control and slewing of a military system
- Thin, large-diameter foils for military systems.

LIST OF TECHNOLOGY DATA SHEETS
6.3. ANTIMATTER PARTICLE BEAMS (APBs)

DATA SHEET 6.3. ANTIMATTER PARTICLE BEAMS (APBs)

Developing Critical Technology Parameter	Antiparticle production: Antiparticle ($\bar{p}$) supply > 0.5 mg/year Antiparticle storage and transfer technology Antiparticle cooling to < 10^{-6} K Production 5 mg/year; ratio (antiparticle/particle) > 10^{-4}. Beam generation, acceleration, and control Need 0.1 to 10 µg per target. Beam neutralization Foil diameter > 25 cm; foil thickness < 20 mg/cm^2. Ion sources Accelerators Injectors Magnetic transport RF power tubes Prime power/power conditioning.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	NC machine tools, antiparticle source preparation technology; copper brazing technology; RFQ design and operation; antimatter production and storage technology; cooling technology-laser cooling.
Unique Software	Computer design and operation code: Magnetic beam line design Precision measuring technology Computer codes for simulating generators (RF).
Major Commercial Applications	Material modification; welding; material testing; new energy sources; advanced propulsion systems.
Affordability	Not an issue.

SECTION 6.4—GAMMA-RAY LASERS

Highlights
• A gamma-ray laser beam (graser) will penetrate deep into a target, unlike visible and IR laser beams, and will be capable of producing a range of lethal mechanism—from soft kill to hard kill.
• A gamma-ray laser weapon is nominally considered for space application—to be used against missiles and satellites.
• Because the gamma-ray laser beam, when developed, will travel at the speed of light, tracking problems associated with slower beams (e.g., PBs) will be avoided.
• The deeper penetration of the high-energy photons in a target overcomes the countermeasures designed against beams that deposit energy on the surface (e.g., long-wavelength lasers).

OVERVIEW

Gamma-ray laser (graser) beam weapons will project coherent EM energy, emitted by specially selected and prepared nuclei, to a distant target at the speed of light. Such beams have been suggested only for exoatmospheric applications; however, they can be used (potentially) from a space platform to attack targets up to about 40 km above the ground. The basic gamma-ray laser has not been developed yet, but, when it becomes a reality, additional system issues will have to be addressed.

This section concentrates on concepts that rely on recoilless processes because these seem to be the most promising. Certainly, more research has been devoted to these concepts, but they are limited to photon energies in the 10-keV-to-100-keV range. Other concepts (i.e., those with the potential of producing more energetic photon beams) have been proposed.

To be able to use these gamma-ray laser beams effectively as weapons:

- Accurate target detection and location are required.
- Accurate beam pointing and control have to be available. This includes beams sensing and steering dynamic alignment and target hit detection.
- The phenomenology of beam propagation, including scattering beam pulsing effects, absorption, and the effect of instabilities, has to be understood and included in the systems analysis.
- Kill assessment is critical to effectiveness and efficiency, especially against multiple targets; therefore, the phenomenology of beam-target interaction has to be understood and folded into the systems analysis.

BACKGROUND

The invention of the ammonia maser in 1954 initiated an era of intense competition in a search for new sources of coherent radiation. The first success was the ruby laser in 1960. Many devices that spanned the spectrum from IR to UV followed the ruby laser. The emissions of these devices were highly directional and of great spectral purity. Much effort was devoted to finding new sources at increasingly shorter wavelengths and higher intensities. The driving forces have included scientific curiosity, the need to observe increasingly smaller structures, improving submicron lithography, and obtaining better DE beams for industrial and military uses. The X-ray regime, which employed atomic transitions, was reached. The search for systems capable of producing lasing with nuclear transitions continues.

The shaded area in Figure 6.4-1 indicates the region of the EM spectrum-of-interest in studies of nuclear superflourescence (SF) in particular and gamma-ray laser research in general. This region stretches roughly from about 1 keV to 100 keV.

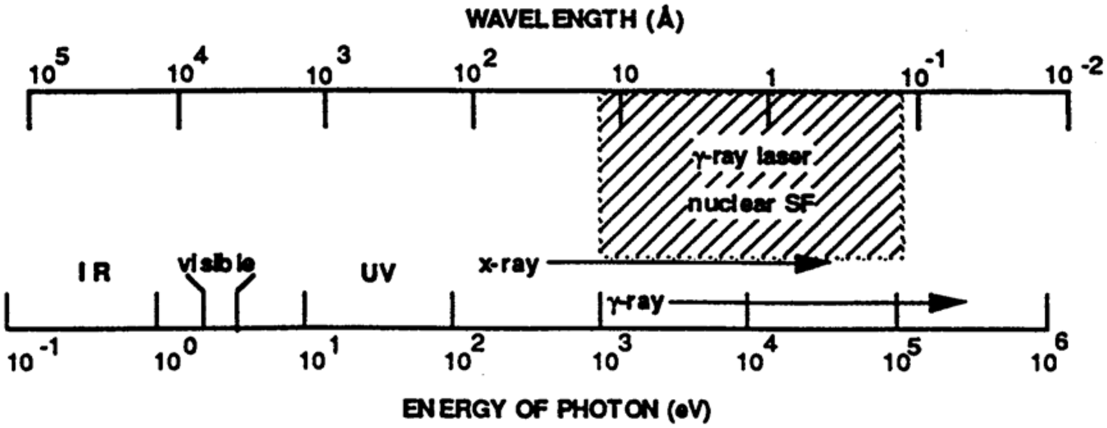


Figure 6.4-1. The Gamma-Ray Laser Region of the EM Spectrum

Photon emission is severely inhibited by competition from internal conversion below 1 keV. Above 100 keV, recoil destroys the resonance between nuclei to such an extent that simple resonance and cooperative processes are suppressed. Working in this high-energy regime introduces problems not usually encountered at lower energies:

- There are no effective mirrors, so that one is forced to consider only single-pulse devices.
- The high recoil normally present during emission and absorption at these energies restricts us to Mössbauer transitions that avoid recoil under very special but well-understood conditions.
- The high attenuation of EM radiation at these energies, largely caused by the photoelectric effect, reduces the gain of a system of nuclei. Fortunately, under special conditions in crystals, the Borrmann Effect has been shown to enhance coupling to the nuclei preferentially (as compared with the electrons) and thus reduce attenuation caused by the photoelectric effect.

These restrictions in the high-energy regime are somewhat counterbalanced by the existence of long-lived nuclear isomeric levels with lifetimes from seconds to years. Isomeric levels permit long pumping times and provide energy storage; however, the long-lived levels have correspondingly narrow natural line widths, which, under normal conditions, worsen the effect of inhomogeneous broadening and reduce resonance.

Recent work in gamma-ray lasers has concentrated on two approaches that use nuclear isomers: the *up-conversion* concept and the *direct-emission* concept. Figure 6.4-2 compares the two concepts.

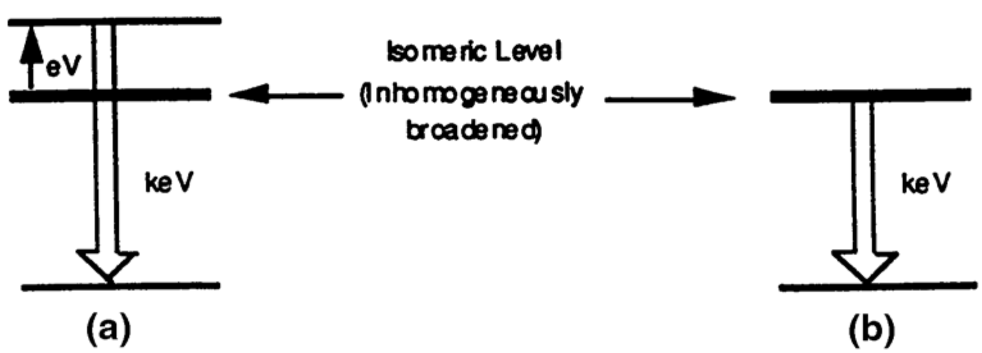


Figure 6.4-2. Energy Level Schemes for the (a) Up-Conversion and (b) Direct-Emission Concepts

The *up-conversion* concept uses the isomer as a storage level [see Figure 6.4-2(a)]. Energy is pumped to up-convert the nucleus to another closely spaced level that acts as the upper level for the lasing transition. The major issues are the identification of the nucleus with a short-lived level near an isomeric level and the power requirements on the pumping laser. No real nucleus that can satisfy these requirements has been located.

The *direct-emission* concept involves preparing a nucleus in an isomeric level that also serves as the upper lasing level [see Figure 6.4-2(b)]. The main concern is the inhomogeneous broadening that prevents nuclei in the inverted population from being on resonance. The size of this inhomogeneous broadening and the means of efficiently reducing it are issues that need to be resolved.

These two concepts have something else in common besides the use of isomeric levels. Both approaches require the Mössbauer transitions for the emission process. The up-conversion concept uses the isomeric level as a storage level. The upper lasing level in this scheme, however, needs to be a strong Mössbauer level. In the direct-emission concept, the isomeric level serves a dual purpose. It has to be long-lived-enough to permit pumping the system to inversion. Since it also serves as the upper lasing level, it has to have those desirable properties of a Mössbauer level. Both concepts present different issues depending on how the isomeric levels are used. In the search to resolve these issues, various approaches have been proposed.

A third concept that has recently attracted some attention is called the *gas graser* concept, or gamma-ray laser with recoil. This concept is revolutionary because it avoids the problem of high recoil in the gamma-ray regime and removes the dependence of gamma-ray lasing concepts on the Mössbauer Effect (recoilless emission and absorption). In this concept, nuclei emit with recoil coherently but only under the extremely low temperatures required to reduce Doppler broadening. The gas graser has been considered before, but cooling technology has only recently reached a state that makes this concept interesting. Presently, 10^{15} atoms can be cooled down to the nano-Kelvin range. Table 6.4-1 summarizes the progress made in laser cooling since 1975.

Table 6.4-1. Laser Cooling of Atoms

Year	Atomic System	Temperature	Comments	Author/Location
1975	(Mg)	0.024 K		Hansch and Schawlow
1983	(Mg)	0.05 K	~ 10^6 atoms	NBS and JILA
1987	(Na)	0.001 K	10^8/cm^2	NBS
1989	(Na)	20 nK	10 cm/sec	Phillips (NIST)
1995	(He)	3 nK		Cohen-Taunodji (Paris) (VACPT)

Potential Gamma-ray Laser Applications

High-energy radiation enables deep penetration of dense materials. In iron, a 1-MeV gamma ray (with an attenuation coefficient of $\mu_a \cong 0.4$ cm^{-1}) has almost 10^6 times the penetration of a 1-keV gamma ray. This feature, together with other characteristic features of photons emitted in nuclear transitions (e.g., high-energy resolution) and the ability to ionize atoms and molecules, coupled to the attributes of a laser beam (e.g., high coherence), would permit good focusing at high intensity. It could also provide a new powerful technique for probing and modifying materials.

Some potential applications of gamma-ray lasers are:

- **Gamma-ray and X-ray spectroscopy.** In this application, higher energy resolution would permit greater discrimination and deeper penetration would permit inspection of thicker samples.
- **Holography.** In this application, short-wavelength coherent radiation might permit observation of the structures of molecules, crystals, proteins, and genes.
- **Precision frequency measurements.** In this application, measurements based on interferometric techniques could be extended to the nuclear region, thus greatly increasing the precision in the determination of nuclear properties (with possible applications to reactor design and fusion investigations).
- **Imaging techniques [e.g., for computerized axial tomography (CAT) scanners].** In this application, monochromatic radiation would permit lower doses to patients, while higher resolution would allow discrimination between molecular species and not just between density variations.
- **Nonlinear optical effects at nuclear energies.** In this application, these effects could be investigated with applications to high-energy particle and nuclear studies.

- **Nuclear reaction modification.** In this application, the high intensity of the highly monochromatic gamma radiation would permit selective removal of electrons and, thus, charge density modification in and around the nuclear volume.
- **Microscopy and structure determination.** In this application, the high intensity would allow short exposures and high collimation would permit Fresnel-limited resolution.
- **Microreplication and fabrication of microelectronic components.** In this application, high intensity and excellent collimation will shorten the exposure time and ensure good resolution.
- **Material science.** In this application, the high intensity of the ionizing radiation will provide massive ionization of materials on a local scale, leading to violent structure modification.

New Technological Developments That Could Impact Laser Development

These new technological developments could have a profound impact on laser development:

- **Lasing without inversion.** This process promotes emission while reducing absorption between the same two levels, leading to lasing without inversion and contradicting the most basic principle of early laser thinking. It has been observed in atomic systems and should be investigated in nuclear systems.
- **"Single atom" lasing.** The transfer of energy between an atom and a cavity has been observed, leading to gain in the output. This operating mode should be investigated for possible application with nuclear systems because it could provide a means of avoiding the inhomogeneous broadening problem. Although one does not normally think of this phenomenon as lasing, it is worth pursuing in nuclear systems.
- **Single-atom manipulation.** Using scanning tunneling microcopy or laser (cooling) technology, single atoms can be arranged in structures not readily achieved through thermodynamic processes or random statistical procedures but easily achieved through deterministic and well-planned steps. These procedures could result in the preparation of samples without impurities and irregularities in structure. Such structures could be designed to take advantage of the Borrmann Effect to reduce photoelectric absorption and the Afaaseev-Kagan Effect to reduce internal conversion.
- **Laser cooling.** The gas graser has been considered before but only recently has cooling technology reached a state that makes this concept interesting. Presently 10^{15} atoms can be cooled down to the nano-Kelvin range. Table 6.4-1 summarizes the progress made in laser cooling since 1975.

Summary Highlights

- A gamma-ray laser beam (graser) penetrates deeply into a target and is capable of producing a range of lethal mechanisms—from soft kill to hard kill.
- A gamma-ray laser weapon is being considered for space application against missiles and satellites.
- Propagation through the atmosphere is a major issue because of attenuation, but a gamma-ray laser weapon located on a space platform can also attack targets as far down as 40 km above the ground.
- Because the gamma-ray laser beam travels at the speed of light, tracking problems associated with slower beams (PBs) are avoided.
- The deeper penetration of the high-energy photons in a target overcomes the countermeasures designed against beams that deposit energy on the surface (e.g., long-wavelength lasers).

REFERENCES

Afanas'ev, A.M., and Yu Kagan, *Soviet Phys.* JETP 21, 215, 1965.

Artna-Cohen, A. *JQSRT40,* 663, 1988.

Baldwin, G.C., J.C. Solem, and V.I. Gol'danskii, *Rev. Mod. Phys.* 53, 1981.

Balko, B., I.W. Kay, and J.W. Neuberger, *Phys. Rev. B 52,* 858, 1995.

Balko, B., I.W. Kay, J.D. Silk, and D.A. Sparrow, *Proceedings of the International Conference on Lasers '94*, 1995, p. 9.

Cohen, L., *JQSRT* 40, 735, 1988.

Collins, C.B., and L.A. Rivlin, "Induced Gamma-Ray Emission," *Laser Physics Special Issue 5*, 2, 1995.

Collins, C.B., L.A. Rivlin, and J.J. Carrol, GARALA's 1st International Gamma-Ray Laser Workshop, Predeal, Romania, 19–23 August 1995, 1997.

Vysotoskiy V.I., and R.N. Kuzmin, *Science and Technology-USSR: Physics and Mathematics Sept (1989–90)*, Translation from Russian of Gamma-Ray Lasers, 1982.

LIST OF TECHNOLOGY DATA SHEETS
6.4. GAMMA-RAY LASERS

DATA SHEET 6.4. GAMMA-RAY LASERS

Developing Critical Technology Parameter	Beam generation: Nuclear SF; amplified spontaneous emission. Wavelength: ~ 10 Å to 0.1 Å (concepts using recoilless emission) ~ 10Å and below (gas graser concept—single phonon emission). Lifetime of isomeric level: ~ 100 sec to 1,000 sec (concepts using direct emission from isomeric level) ~ 1,000 sec and above (up-conversion concepts). Temperature: $\sim 10^{-9}$ K (for gas graser concept). Energy stored/power out (depends on transition energy): $> 5 \times 10^{8}$ J/cm^{3} $> 5 \times 10^{10}$ W. Beam intensity: $> 5.0 \times 10^{11}$ W/cm^{2}. Status: Gamma-ray laser is in theoretical state. Concept is in development state. Some recent experimental work on the up-conversion concept claimed the observation of enhanced emission from the hafnium (Hf) isomer. This is controversial. Developments in nanotechnology show promise for preparation of clean (very low-level inhomogeneous broadening) samples and specially designed crystals for active media to reduce attenuation. This would enhance the possibility of observing lasing using the concept of direct emission from isomeric levels.
Critical Materials	Isomeric nuclei with closely spaced levels (0.1 eV to 100 keV); isomeric nuclei with Mössbauer transitions.
Unique Test, Production, Inspection Equipment	NC machine tools; nuclear source preparation technology; precision nuclear measurements; ultralow temperature technology ($< 10^{-9}$ K); technology for manipulation and control of individual atoms.
Unique Software	Computer design and operation codes; accelerator cavity alignment inspection code; B-field mapping codes; computer codes for accelerator design; magnetic beam line design.
Major Commercial Applications	CPB fusion; inertial fusion; nuclear defense simulation and hardening test; welding; material forming.
Affordability	Not an issue.

SECTION 6.5—KINETIC ENERGY WEAPON (KEW) SYSTEMS

Highlights

- For KE weapons, massive kill is projected since projectile produces catastrophic destruction.
- For missile deployment, KEWs need to span a velocity range of 1 km/sec to 14 km/sec and weigh from 10 kg to 10,000 kg.
- For KEW systems, computer simulations are used to determine lethality in situations where tests are costly or otherwise impractical.

OVERVIEW

Most of the information for this section comes from the 7th Electromagnetic Launch Symposium, held in San Diego, California, April 20–24, 1994. This conference dealt with the physics and engineering problems concerned with accelerating small and large objects to velocities in excess of several kilometers per second, and the integration of these EM launchers into mobile platforms.

Hitting a target with a projectile is an effective, established technique of destroying the target through the transfer of KE to the internal modes or structure of the target. Usually, one considers a fast projectile hitting a slower target. For ballistic missile defense (BMD), the opposite is generally the case. Missiles and RVs travel at velocities that enable them to be killed effectively by placing something heavy in their path. The methods described in this section use KE to effect a kill and depend on the collision's KE to be higher than the cohesive energy of the solid target. The problem lies in arranging the collision at a sufficient energy to break the bonds holding the structure together.

KEW systems include EML systems (e.g., railguns and coilguns), ETC guns, and ET guns. Compact pulsed power sources are a common requirement for the weaponization of EML, ETC, and ET guns. Additional improvements to EML systems are the development of wear-resistant materials and supporting structures, enhancements to ETC guns and nonsensitive propellants, and more efficient plasma ignition propellants. Enhancements to ET guns will require more efficient plasma generators.

For an effective kill, the target has to be tracked, and KEW intercept has to be arranged. For attacking a booster, the rocket plume's brightness serves as the target for IR homing devices. For post-boost vehicles, the plume is not normally available, so other sensors need to be used to detect the target. In the terminal phase, ground-based phased-array radars could track RVs and decoys and provide target information for KEWs.

The ability to destroy a target requires a theoretical understanding of the way various projectiles interact with the structure and the experimental confirmation of the theories. The development of theoretical models and related computer programs that analyze the penetration of generic projectiles (e.g., long rods, spheres, and so forth) is basic science. Experimental results of hypervelocity that impact on generic structures are also considered basic science.

BACKGROUND

This section covers technologies for KE projectiles that can destroy or damage targets by using their own KE derived from their own chemical or nonchemical sources. We are considering projectiles of "sufficient" KE to rupture a target permanently or cause its mission to be aborted (e.g., an incoming cruise missile, tank, ballistic missile, and so forth).

We can examine the basic idea of using a projectile to damage a target by considering the collision of two bodies of unequal masses and initial velocities. The total KE before impact is

$$E_o = \frac{1}{2} m_1 V_1^2 + \frac{1}{2} m_2 V_2^2 \quad , \tag{1}$$

where the subscript 1 refers to the target and the subscript 2 refers to the KE projectile.

We consider two scenarios. In the first scenario, there is an elastic collision. The two masses stay together after impact and move as a body of mass $m = m_1 + m_2$ (neglecting debris emission). The final energy of the combined mass is

$$E_f = \frac{1}{2} mV^2 \quad , \tag{2}$$

where V is the magnitude of the final velocity. Neglecting debris effects, from the conservation of momentum and energy, we can get the final KE of the system and the amount of energy available for internal damage to the target:

$$\Delta E = \frac{1}{2}\left(\frac{m_1 m_2}{m_1+m_2}\right)V_R^2 \quad , \tag{3}$$

where V_R is the magnitude of the relative velocity between the projectile and target,

$$V_R = \left|\vec{V}_1 - \vec{V}_2\right| = V_1 + V_2 \quad . \tag{4}$$

ΔE is the maximum energy that is available for internal destruction and debris emission from the surface in this first scenario. An important feature of a KEW is that ΔE is applied in a local area, initially no larger than the cross section of the projectile. For large values of ΔE, the pressures produced in the structural membranes of the target can greatly exceed its internal strength, thus producing permanent damage. This can be much more effective than pressure effects produced by conventional, ordnance-developed blast waves.

In the second scenario, the projectile tears out a section of the target and essentially creates a hole in the target. In the final state, a combined "partial" target mass and projectile travel together at a different velocity from the leftover target (i.e., the one with the hole in it). The damage mechanism is clearly different in this scenario and is critically dependent on the location of the hole. According to cratering theory for simple systems and supported by computer simulation studies for complex systems, the probability of the second scenario increases with the velocity of the projectile.

These two scenarios serve to point out that velocity alone is not a unique measure of the effectiveness of a KEW, and neither is the mass of the projectile, the momentum, or the KE. This is especially true when complex structures are involved (e.g., RVs with a large number of canisters and KE weapons with complex structures, guidance systems, and warheads). For these complex systems, an ongoing argument persists about the actual functional dependence of the "lethality scaling law"(if it exists).

KINETIC ENERGY (KE) PROPULSION SYSTEMS

KE propulsion systems fall into two categories: those used to propel the weapon and those used to test the weapon (often scaled-down versions of the weapon).

KE propulsion systems include the categories of power supplies, power conditioning and storage, and launcher and barrel. Advanced energy and power conditioning technologies are essential to operating KEWs that have a capability exceeding conventional munitions. Improvements in batteries, capacitors, inductors, pulse compression networks, homopolar generators (HPGs), and compulsators can support this goal.

Batteries store energy in the chemical bonds formed by reactions between the electrodes and electrolytes and tend to have a relatively high internal resistance that restricts their rapid discharge. The newer lithium batteries have lower internal resistance for faster discharge capabilities and can store higher energy densities than normal batteries.

Capacitors store energy in the electric field set up across their dielectric by the disposition of positive and negative charges. Capacitors amplify current, charging at low currents and discharging at high currents (same voltage level). Electrolytic capacitors are relatively small-energy, low-voltage devices (700–2,000 V). Capacitors are available with voltage ratings up to 100 kV.

Inductors store energy in the magnetic field set up around a current-carrying conductor and can generally store higher energy densities than capacitors. Inductors essentially amplify the voltage while keeping the current constant. However, since they have shorter time constants than capacitors, they internally dissipate stored energy faster. Cryogenically cooling the inductor drastically reduces its internal resistance but still only increases the time constant from milliseconds to seconds, whereas capacitors can store energy for 1,000 sec or more.

Pulse forming networks (PFNs), consisting of capacitors and/or inductors connected by appropriate switches, accept input power at a low level and store and sequentially discharge this power at subsequent stages [at a higher power level and a shorter (compressed) pulse time].

An HPG is a variant of a direct current (DC) machine. In its simplest form, it is a Faraday disc rotated in an axial magnetic field. The rotor is brought up to speed by an externally applied torque, and KE is stored in the rotating disc. Then, the external drive is removed, and the HPG becomes a generator as the conductive disc rotates in the magnetic field and the external circuit load is applied.

A compensated pulsed alternator, or compulsator, is a variant of the simplest alternating current (AC) synchronous machine, which has its output generated in a rotating armature winding (usually in the 10- to 15-kV range). The compulsator incorporates an additional stationary winding, which is connected in series with the rotating armature winding. This compensates for the internal inductance at one point in each cycle (usually at peak voltage, where the windings are opposed and the inductance is a minimum), at which point the internal impedance is minimum and a fast (submillisecond) pulse of current output is generated.

LAUNCHER AND BARREL SYSTEMS

The launcher and barrel systems discussed in this section are classified as electric armaments. The major types can be grouped in the general categories of railguns or rail accelerators, pulsed electrothermal (PET) and plasma propulsion, and coilguns or coaxial launchers. Each category has variations of the basic concept (e.g., solid armature railguns, plasma armature railguns, augmented railguns, ET guns, combustion-augmented ET guns, hybrid guns involving a combination of thermal electric and plasma armature railguns, and so forth).

Railguns or Rail Accelerators

KE systems using EM propulsion use large-current pulses to accelerate a mass to a velocity that is many times the velocity possible with conventional propulsion. Some of the advantages in using EM propulsion instead of chemical propulsion are higher velocities and a more uniform acceleration, blast and signature reduction (although the introduction of a stronger EM signature needs to be considered), ease of projectile control and flexibility of projectile geometry, and lower vulnerability (caused by lack of propellant charges). The major critical areas are rail erosion/consumption and stiffness requirements for launching tubes.

For example, light gas guns (LGGs), using low pressure helium, are used to inject projectiles into the railgun with initial velocities on the order of 0.5 km/sec. Also, distributed-energy-store (DES) systems are being investigated to inject current into the railgun at intervals along its length. These DES systems are triggered to synchronize with the passage of the accelerating projectile. A multistage system has also been built. In addition, techniques for increasing the inductance per unit length of the rails are being considered [e.g., constructing a stacked (n-turn) railgun].

Pulsed Electrothermal (PET) and Plasma Propulsion

ET propulsion and ETC propulsion have the potential for numerous military applications, and certain aspects of this technology should be protected. These propulsion concepts consist of a pulsed electric discharge that evaporates material in a chamber and heats the material. The resulting high-pressure gas (plasma) expands through a nozzle or barrel, where it can be used as thrust to propel a rocket or to drive a projectile.

Electrically driven cartridges are used to fire projectiles at hypervelocities using conventionally designed reusable gun barrels. This technology is essentially an extension of classical gun technology. The cartridge device makes use of a high-impedance capillary plasma jet situated inside the cartridge or breech block. This enables electrical energy to be injected efficiently into a relatively cool, low-atomic-weight propelling fluid. Various power supplies (e.g., a capacitive PFN, homopolar-inductor system, or compulsator) can drive the cartridge. Pulse shaping of the delivered power can be designed to maintain nearly constant pressure projectile acceleration compatible with the barrel strength. The major critical issue is controlled plasma generation.

Coilguns or Coaxial Launchers

Coaxial launchers have not received as much attention as railguns, but they have many advantages. Current-carrying loops on the projectile and in the coaxial accelerator develop magnetic fields that interact to either push or pull or push and pull the projectile along the loop. Synchronized switching controls currents. These current-carrying loops may or may not require physical contact with the projectile, can be scaled to large diameters, can distribute thrust over the length of the projectile, and offer higher efficiency. One of the limiting technologies is high-voltage switching for high velocities. The major critical issues are synchronization of current injection, projectile design, and heating.

PROJECTILES

KE systems depend on the KE of their projectiles to destroy or degrade the target. Consequently, the projectiles are as critical to the system as the propulsion components are. Conceptually, KE projectiles cover the spectrum from small grains of ablative material propelled by lasers at a velocity of 100 km/sec, to large rocket-launched devices such as the Homing Overlay projectile, which closes with a ballistic missile warhead at the relatively low velocity of approximately 6 to 14 km/sec or higher. The commonality of such widely varying projectiles (i.e., destroying or degrading the target by KE) shows the range of projectile characteristics.

The technologies associated with KE projectiles are as diverse as the projectiles. If propelled in the Earth's atmosphere, projectiles with velocities over approximately 4 km/sec must be cooled by active systems. At velocities less than 4 km/sec, passive cooling, such as ablative coatings, can be used. Unless projected at targets in very close range (e.g., in a point defense application), projectiles require in-course guidance. This is a major difference between KE and DE systems. The latter projects beams at nearly the speed of light. These beams of light hit where they are aimed. Extremely small, high-velocity KE projectiles can be guided to the target by laser beams. Larger projectiles must incorporate sensors [infrared (IR), optical, radar] to guide them to the target; thrusters or other devices to alter their course; fuel for the thrusters; and possibly a computer to translate sensor inputs to thruster direction and power.

Projectiles incorporating complex cooling and guidance components will be heavy. The resulting weight will limit the velocity at which a given energy level can propel the projectiles. Consequently, technologies to miniaturize sensor and guidance systems and technologies to increase the energy levels of projectors must be pursued together.

KINETIC ENERGY (KE) TARGET EFFECTS, TEST TARGETS, AND COUNTERMEASURES

This section also addresses technologies to maximize the effect of KE system projectiles on the target and all aspects of development, production, use, and post-test evaluation of physical targets and models. Test targets and models are defined as the physical and analytical embodiment (or portions thereof) of the KEW systems or potential targets.

The study of hypervelocity impact on structures has been conducted with various levels of intensity for 40 years. R&D has focused on the areas of antiballistic missile technology, meteoroid impact on space platforms, and the use of ultrahigh pressures to simulate nuclear weapons effects. More recently, the application of KEW to pierce heavy armor and to destroy incoming antiship cruise missiles (ASCMs) has generated some interest.

SIMULATIONS AND MODELING

Military interests have driven the physics of impact in large part—from a defensive and an offensive role. The contest between faster projectiles and stronger armor has been the principal motif in military history. In an attempt to build more effective weapons, understanding the interaction between projectiles and targets has been the goal of designers, builders, and testers. Today, this understanding is usually achieved through a combination of experimental work and computer simulations. However, we have reached a point where experimental techniques are inadequate to examine the areas of interest to weapon designers and policy planners.

The recent interest in hypervelocity projectiles with velocities of 5 to 10 km/sec has forced researchers and decision-makers to rely more heavily on computer simulations because the cost and inherent difficulties of conducting the experiments to get the desired data are prohibitive. Also, for some cases, equipment is not even available to generate the appropriate conditions of high KE. Consequently, reliance on computer codes has been growing, and the development of physics-based codes has been supported. Researchers feel that these codes, which are based on sound physical principles, should provide accurate predictions of lethality under diverse conditions.

To supplement live-fire testing, the Services and the Ballistic Missile Defense Organization (BMDO) have developed several codes. Two types of computer simulations have been involved: physics-based codes and engineering codes based on empirical results and divers theoretical models.

Summary of Simulations and Modeling

The advantage of computer modeling is that high-resolution temperature, density, and pressure profiles can be made available to the analyst and weapons designer. Such high-resolution data are impossible to get from experiments. However, computer speed and memory and limited knowledge of material properties at extreme conditions limit the computational approach.

Scaling problems complicate sub-scale testing. Relating the results to full-scale conditions is difficult because of the nonlinear nature of the phenomena being examined.

Another approach could be invoked. This approach would involve full-scale testing of subsections of the larger system together with computer modeling of the interactions of the subsections forming the total system. The results of the testing could be included in a computer model dealing with a full-scale interaction. The computer code would be the glue that would model the interactions between the subsystems.

LIST OF TECHNOLOGY DATA SHEETS
6.5. KINETIC ENERGY WEAPON (KEW) SYSTEMS

DATA SHEET 6.5. KINETIC ENERGY WEAPON (KEW) SYSTEMS

Developing Critical Technology Parameter	For missile defense, KEW systems of current interest span intercept velocities and vehicle masses over a wide range, depending on the defense scenarios for which they are designed. The range of parameters is: Velocity: from 1 km/sec to 14 km/sec Mass: from 10 kg to 1,000 kg. For ground targets (tanks) and airplanes, KEWs at lower velocities and masses are required. The range of parameters is: Velocity: from 100 m/sec to 2,000 m/sec Mass: from a few grams to kilograms. For test purposes, high-velocity launchers are available to accelerate low masses at high velocities (two-stage LGG for 0.002 kg at 8.5 kg/sec) and higher masses at low velocities (10 kg at 1 km/sec, also an LGG). However, at present, launchers are not available to accelerate high masses at high velocities as required by current concepts.
Critical Materials	High-tensile-strength materials and composites for armor; high-density materials.
Unique Test, Production, Inspection Equipment	Propulsion systems.
Unique Software	Software for determining lethality after intercept: Hydrocodes Engineering codes Special material properties databases.
Major Commercial Applications	None identified.
Affordability	Not an issue.

BACKGROUND

Unlike HELs and PB systems, KE projectiles travel at high velocities but much slower than the speed of light; yet, they have sufficient KE to rupture permanently and disrupt all types of targets or cause the mission to be aborted. The technologies associated with KE projectiles are as diverse as the projectiles. If propelled in the Earth's atmosphere, projectiles with velocities over approximately 4 km/sec must be cooled by active systems. At velocities less than 4 km/sec, passive cooling, such as ablative coatings, can be used. Unless projected at targets in very close range (e.g., in a point defense application), projectiles require in-course guidance. This is a major difference between KE and DE systems. The latter projects beams at nearly the speed of light. These beams of light hit where they are aimed. Extremely small, high-velocity KE projectiles can be guided to the target by laser beams. Larger projectiles must incorporate sensors (IR, optical, radar) to guide them to the target; thrusters or other devices to alter their course; fuel for the thrusters; and possibly a computer to translate sensor inputs to thruster direction and power.

Projectiles incorporating complex cooling and guidance components will be heavy. The resulting weight will limit the velocity at which a given energy level can propel the projectiles. Consequently, technologies to miniaturize sensor and guidance systems and technologies to increase the energy levels of projectors must be pursued together.

SECTION 6.6—HIGH-POWER MICROWAVE/RADIO FREQUENCY (HPM/RF)

Highlights

- HPM/RF weapons use EM waves as a DE beam under a variety of battlefield conditions.
- HPM/RF weapon EM signals that enter military systems through unconventional and inadvertent pathways can cause permanent damage and temporary upset to mission-critical equipment.
- Two basic categories of HPM/RF weapons are wide band (WB) and narrow band (NB). The WB weapons produce an impulse-like waveform at the target. The NB weapons produce a modulated sinusoidal waveform at approximately a single frequency. The NB weapon bandwidth is a few percent of the center frequency.
- HPM/RF weapons can be land, sea, or air based or used as a launched munition.
- Getting closer to a target increases the peak electric field and total energy flux that strikes the target, which, in turn, increases the possibility that an HPM/RF weapon can adversely affect a target.
- The efficiency of an HPM/RF source is a critical parameter. Currently, most sources have low efficiency, with some approaching the 30- to 50-percent range. Low efficiency means larger power sources, with a corresponding increase in weight and volume. In addition, the high antenna gains necessary to achieve high effective radiated power (ERP) require large antennas. These factors complicate logistics and mobility.
- Building HPM/RF weapons requires advances in making the following components more compact and energy efficient: prime power sources, high-peak-power and/or average-power microwave sources, pulse power systems, and high-gain antennas.
- The average and peak power capability for NB sources is expected to increase by roughly a factor of 3 every 5 years.
- Because U.S. systems (e.g., GPS, electrical utility power grids, air defense, and so forth) rely so heavily on networks and systems of networks, they may be particularly susceptible to and vulnerable against HPM/RF attacks.
- Major innovations and breakthroughs in testing and simulation are required to predict successfully the susceptibility of systems against HPM/RF threats.

OVERVIEW

HPM/RF technology deals with the use of intense RF waves as DE against military targets or segments of civilian systems that support military operations. This form of DE is capable of being delivered on target either as a series of pulses or as a CW. This section emphasizes the frequency range above 100 MHz and extending into the lower part of the microwave region. According to the Institute of Electrical and Electronics Engineers (IEEE), the microwave frequency band extends from 300 MHz to 300 GHz. In the DEW context, the HPM frequency band covers the frequency range from about 100 MHz to about 5 GHz. We define this region by the term high-power microwave/radio frequency or HPM/RF. For military systems, most interest will be in the 200-MHz to 5-GHz range. HPM also has the following DEW attributes: at the radiating antenna, it can generate either a peak ERP level of 100 MW or more, a single pulse of effective radiated energy of 10 J or more, or an average ERP level of 1 MW or more.

The concept of using EM energy in military combat is not new. For example, jamming and/or spoofing radar and communication receivers by overpowering them with man-made noise and other unwanted signals dates back more than 60 years. This use of RF as a weapon has traditionally been termed EW (electronic warfare). Today, this military use of RF is also called IW (information warfare).

Traditional EW techniques make no attempt to destroy physically the electronic components of radar, communication, or navigation receivers or any other RF sensor. In the typical military scenario, relatively low-level unwanted RF signals (as compared with those levels that could rupture electronic components) are usually sufficient to reduce or eliminate the ability of RF receivers to discern the desired information from the combined desired-plus-unwanted signals.

HPM/RF DE signals are intended to affect systems adversely because of their higher power density and/or energy density on target but to do so with less knowledge about the system's susceptibility than that required for typical EW signals. HPM/RF signals can disrupt the normal operation of some military information systems by mechanisms that involve inserting incorrect information into the electronics or causing the disruption of individual electronic components.

Unwanted EM signals that adversely affect the performance of military systems by entering through receiving antennas are said to enter through the "front door." Those that manage to cause system malfunction by entering through inadvertent apertures, such as seams in doors and exposed cables, are said to enter via the "back door." HPM/RF signals generally enter the electronics via the "back door" but can also be an out-of-band threat to RF receivers.[1]

Traditional EW is usually designed to defeat a single system or a single class of systems. The goal of HPM/RF is not necessarily to have a specific unwanted waveform for a specific target, but rather to have a few classes of waveforms that can attack many different systems.

RF receivers and sensors are normally designed to be sensitive enough to pick up weak friendly signals. When the voltage threshold settings of these receivers are set at small values, they become more susceptible to HPM/RF interference and damage. The interference may also spoof the target system.

A major distinction between traditional EW and HPM/RF is that EW-class signals do not normally cause permanent effects. All in all, upset is more important than permanent damage because it occurs typically more than an order of magnitude lower in field strength and about two orders of magnitude lower in power.

Figure 6.6-1 will help to bring the relationship between system susceptibility, EW, and HPM/RF into sharper focus. This figure shows, in general terms, the relationship between the RF power required to affect a system adversely and the knowledge of the target. At the upper left-hand corner is the EW domain. Here, we know quite a bit about the target and need relatively little energy because we can focus the energy in the required frequency band and with the required modulation. On the other hand, with minimal knowledge about the target, a relatively large amount of power is needed because we have to cover a wider frequency region. This domain is shown in the lower right-hand corner.

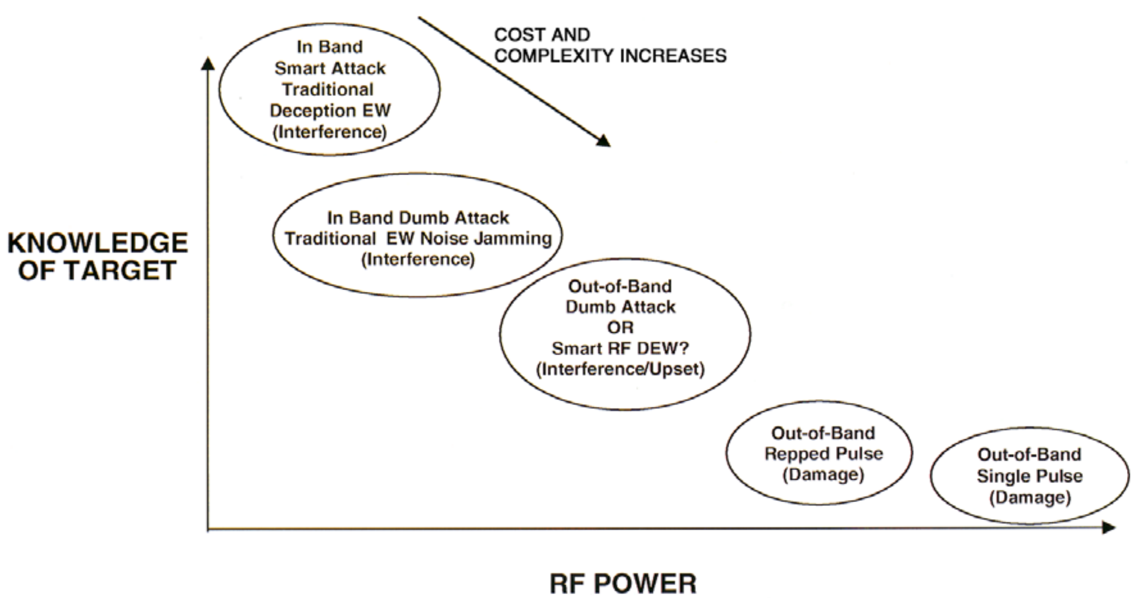


Figure 6.6-1. Knowledge of Target and Required RF Power

---

1 Out of band refers to the HPM/RF signal being out of the pass-bands of the system's antennas and receivers.

The HPM/RF technologies divide naturally into two major groups: Offensive Technologies and Defensive Technologies. With few exceptions, the technologies in these groups are different from each other. The Offensive Technologies are concerned with inflicting damage on a system whereas the Defensive Technologies are concerned with mitigating the effects of the unwanted signals. As shown in Table 6.6-1, each of these groups consists of nine technology areas, and each area has many individual items.

Table 6.6-1. Offensive and Defensive Technologies

Offensive Technologies	Defensive Technologies
• NB HPM sources	• Susceptibility and system response
• Pulse compression	• External EM coupling
• WB HPM sources	• Internal EM coupling
• Antennas	• EM topology
• Switching	• Simulation and modeling
• PFNs	• System testing (survivability)
• RF munitions	• RF hardening
• Propagation	• Survivability assessment
• Lethality Assessment	• System testing (lethality)

HPM/RF Offensive Technologies share some common interests with Energy Systems Technology in the following areas: high-speed switching, PFNs, and energy storage (see Section 7). The synergism between Energy Systems Technology and these three technology areas stems from the fact that generating and radiating HPM/RF is a pulsed-power problem. Some top-level overlap also exists between Sensors Technology (see Section 17) and the area of pulse compression. In Sensors Technology, the interest is in conventional radar. The significant increase in power for HPM/RF compared with the power necessary for conventional radar limits the depth of commonality between these two sections.

International cooperation for HPM/RF Offensive Technologies is limited principally to developing sources that can provide higher average and peak power levels and greater flexibility in waveform design and modulation. Cooperative agreements exist with a few countries, notably some of our NATO allies and Russia.

HPM/RF Defensive Technologies have some overlap with Weapons Effects Technology (see Section 20). This significant commonality stems from two causes:

- First is the considerable overlap in predicting the unwanted EM fields that penetrate into a target system between the high-altitude electromagnetic pulse (HEMP) threat and the HPM/RF threat.
- Second—and perhaps the most relevant—is that the host of EM coupling problems and remedies introduced by HEMP has been incorporated into the international electromagnetic compatibility (EMC) and electromagnetic interference (EMI) communities. These technical communities routinely hold international meetings and symposia to evaluate technical progress.

Because of the indirect way that HPM/RF signals enter into a system, the knowledge and experience in understanding how these signals affect the operation of computer and telecommunication networks are limited. However, these kinds of networks are the backbone of contemporary military information systems. A major Defensive Technology that needs to be addressed in the near future is to determine how the different HPM/RF waveforms affect the operation of computer and telecommunication networks. This understanding will require quantitative analyses of information flow and how unwanted signals affect this flow. A related major concern is to design tests that evaluate the systems' survivability against different waveforms and to interpret the results of such tests to determine the systems' survivability. To accomplish survivability assessment in a cost-effective way, a required technology is the development of statistical techniques that predict—with a minimum number of tests—the levels of survivability against HPM/RF.

BACKGROUND

The first ubiquitous observation that large unwanted EM fields could cause permanent physical damage or long-term upset to electronic devices is attributed to the naturally occurring phenomenon of lightning. Lightning is a sequence of a few relatively slow single pulses. Although the pulse length and frequencies associated with lightning are vastly different from HPM/RF waveforms, the idea is similar: a huge pulse of energy enters the system and via a multitude of obvious and not-so-obvious EM paths and causes damage to devices and circuits. Theoretical studies of the EM field effect produced by a high-altitude nuclear detonation—the HEMP waveform threat—were conducted in the 1960s. Like lightning, the HEMP waveform is a single pulse; however, it differs substantially in duration and frequency content. In a sense, HEMP can be regarded as a man-made analogue to lightning.

Theory showed that the HEMP at ground level could penetrate into military systems by inadvertent antennas (e.g., a hydraulic control cable that runs from the interior of the fuselage into the wings of an aircraft) and apertures (e.g., the cockpit window of an aircraft). The theoretical predictions of HEMP damage to systems were confirmed by experiments conducted on actual electronic systems in the 1970s and 1980s using newly developed system-level HEMP simulators. The intensity of this unwanted EM field produced by the HEMP was strong enough to damage internal circuitry physically and disrupt the flow of information.

By the early-to-mid 1970s, HPM/RF sources emerged. The power level of these new sources was much higher than the power level of conventional microwave radar sources (e.g., klystrons and magnetrons) produced up to that date. Based on the experience and knowledge gained from HEMP tests about the deleterious effects of strong unwanted EM fields, it was proposed that similar effects could be achieved using these new powerful HPM/RF microwave sources. By coupling the output of these sources to high gain and, hence, NB directional antennas, the concept of using HPM/RF as a DEW was created.

Table 6.6-2 compares the salient features of Radar/EW/EMI, HEMP, lightning, NB HPM, and WB HPM and shows their effect on systems. A more appropriate name for WB HPM is high-power impulse (HPI). We will use this terminology in future sections when we want to stress the importance of the impulse nature of the waveform. For NB HPM a figure of merit is the peak power density at a specific range. For HPI, the figure of merit is the range-electric field product, *rE*.

Table 6.6-2. Comparison Between Radar/EW/EMI, Lightning, HEMP, NB HPM, and WB HPM

	Environment				
Parameter	**Radar/EW/EMI**	**HEMP**	**Lightning**	**HPM* (NB)**	**HPM (WB)**
Typical frequency	200 kHz to 35 GHz	DC to 100 MHz**	DC to 10 MHz***	100 MHz to 5 GHz	100 MHz to 3 GHz
Typical peak power density (W/cm^2)	Up to 10 (at 10 m)	650 (CONUS-wide)	Up to 750 (at I km)#	Up to 10^4 (at 1 km)	–
Range-electric field product (Volts)	–	–	–	–	~ 1 MV
Typical pulse-width	10 ns to CW	Hundreds of nano-seconds to seconds	500 ns to 100 ms	10 ns to 1 ms	0.3 ns
System effect	Interference, degradation, or mission upset	Upset and damage	Upset and damage	Upset and damage	Upset and damage

Notes for Table 6.6-2:

* All HPM parameters are not received simultaneously.
** Typical bandwidths per event.
*** Typical bandwidth of an event.
\# From a severe cloud-to-ground lightning strike (200 kA peak current).

HPM/RF DE systems encompass a wide range of waveforms and a correspondingly wide range of supporting technologies. Figure 6.6-2 shows these options. In this figure, the two primary HPM/RF technologies are the WB and NB. Explosively driven RF sources remain of interest, but, at their current stage of development, they have limited applicability.

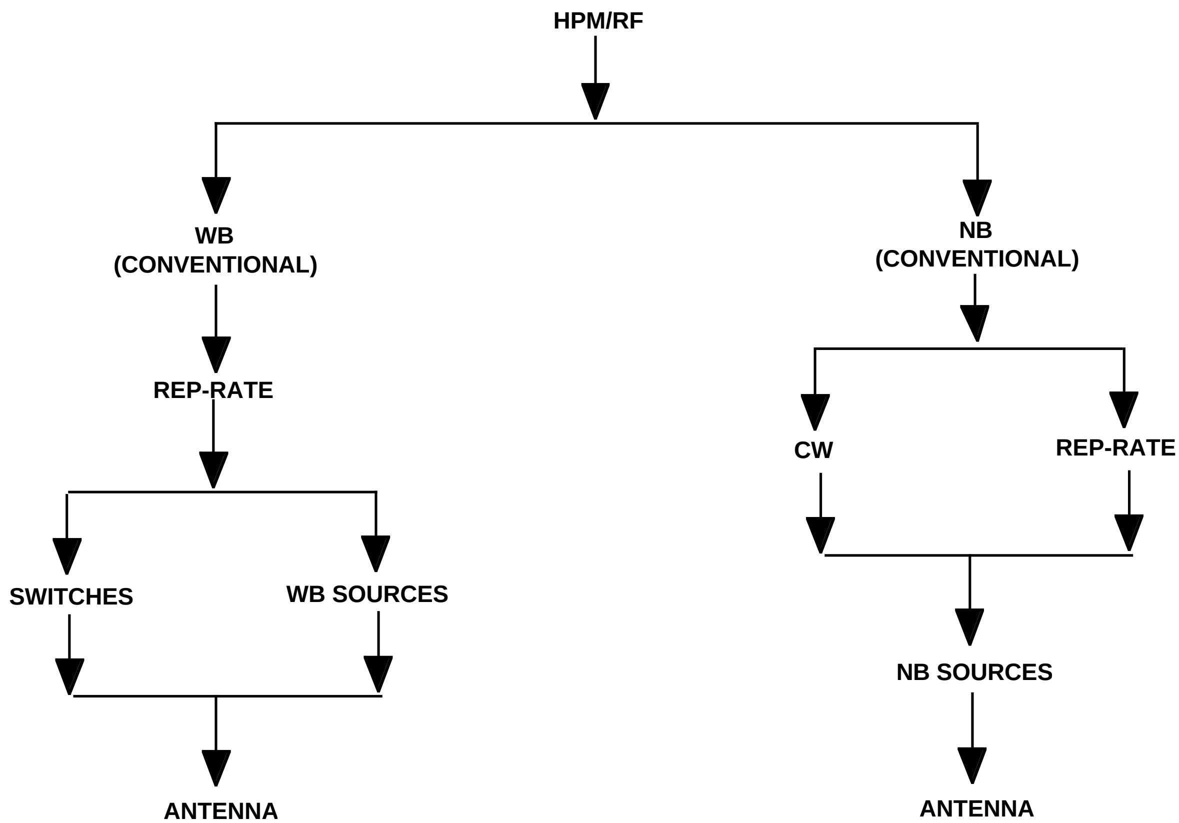
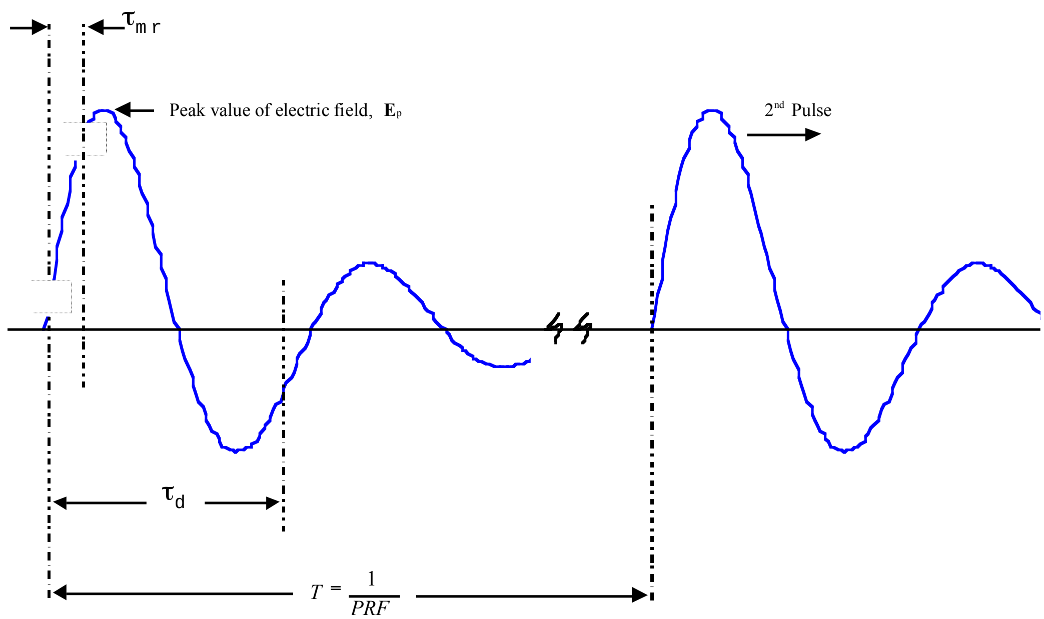


Figure 6.6-2. Taxonomy of HPM/RF Systems

WB pulses have broad frequency coverage but low energy content per frequency interval. The shortness of the pulse produces the WB waveform. These pulses are based on impulse-like waveforms. They are an approximation to the ideal impulse function (the delta function). In some cases, the WB waveform could resemble a damped sine wave of a few cycles. A WB HPM/RF signal can be either a single pulse or a repeated pulse. Figure 6.6-3 is a WB waveform that resembles a damped sine wave of a few cycles. The four main features of the waveform are the risetime, τ_{mr} ; the pulse width, τ_d ; the peak value of the pulse's electric field, E_p ; and the pulse repetition frequency (PRF). The risetime for a WB signal is the ratio of the peak value of the signal to the peak value of the time derivative of the signal. The bandwidth is approximately the reciprocal of the risetime. The pulse duration is not precisely defined. It represents the amount of time that significant energy is contained in the pulse. For the pulse indicated in Figure 6.6-3, the pulse duration is one or two times the risetime. For other types of sources, such as a damped sine wave, the pulse duration could be an order of magnitude larger than the risetime.

An HPM/RF system's primary energy source has a finite average power limitation. An HPM/RF system is, therefore, also limited by an average power constraint. This means that there is always a tradeoff between the energy available in a single pulse and the PRF: the higher the energy contained in a single pulse, the lower the PRF will be.

WB HPM/RF signals are, by their nature, more likely to cover frequencies that can couple to a system. However, because the energy in the pulse is spread out over all the frequencies, the content in any narrow frequency band is inherently low. Thus, even though a target system may have a strong resonance for the absorption of unwanted EM energy in a narrow frequency band, the amount actually absorbed may be too low for it to be effective. In cases



Parameter	Comments
Risetime, τ_{mr}	Typical times are in hundreds of picoseconds.
Pulse width, τ_d	Time in which significant energy in the pulse persists. This varies from a few τ_{mr} to about $10\tau_{mr}$.
Peak value of pulse's electric field, E_p	Depends on distance from source. Could be tens of kilovolts/meter at 10 m from source. E_p varies as 1/R, where R is range from source.
Pulse repetition frequency (PRF)	Varies from single shot to the low kilohertz range.

Figure 6.6-3. Key Parameters of a WB Pulse

Note for Figure 6.6-3: *T = interval between pulses; PRF = pulse repetition frequency.*

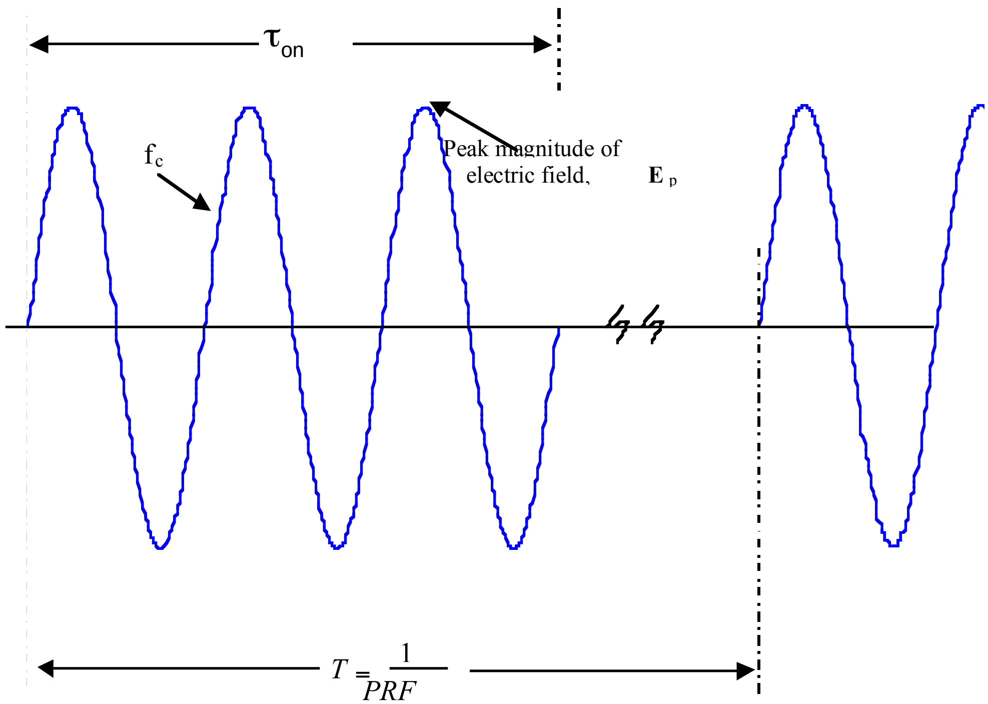
like this, using a waveform that is better tuned to the target is a more prudent alternative. This latter class of waveform is an NB pulse.

Figure 6.6-4 shows the key parameters of an NB pulse. These include the carrier frequency, f_c ; the on-time, τ_{on} ; the amplitude of the pulse, E_p ; and the PRF. When the on-time equals the reciprocal of the PRF, we have a CW. Theoretically, a CW has zero bandwidth—the ultimate NB signal.

Up to this point, we have described HPM/RF and stated that unwanted HPM/RF signals could disrupt the operation of electronic systems by causing upset and/or permanent damage to electronic components. We showed that HPM/RF technologies could be broken down into two groups: Offensive Technologies, which are concerned with delivering EM energy on target, and Defensive Technologies, which are concerned with the effect this intensemicrowave energy has on military electronic systems and the techniques that are required to mitigate the effect.

Future military systems will require electronic hardening against HPM. Significant cost savings can be gained by inserting electronic hardening techniques during the initial manufacture of a system rather than retroactively inserting them after the system has been fielded.

Even though a revolution in HPM/RF sources and related radiation systems technologies may not be forecasted, the impact of realizing the full potential of existing concepts may still be significant. The U.S. Government is currently evaluating and assessing several source concepts covering WB and NB possibilities. Little research is being conducted to support explosive RF sources.



Parameter	Comments
Carrier frequency, f_c ;	Typically ranges from 100 MHz to 5 GHz.
On-time, τ_{on}	Duration in which the carrier frequency waveform is on. Can vary from microseconds to seconds. Continuous operation occurs when τ_{on} = T.
Amplitude of the pulse, E_p	Highly variable. Depends on distance from source, on-time, and PRF.
Pulse repetition frequency (PRF)	Varies from tens of hertz to kilohertz.

Figure 6.6-4. Key Parameters of an NB Pulse

Note for Figure 6.6-4: *T = interval between pulses; PRF = pulse repetition frequency.*

Mitigating the effects of incident EM radiation on a military system such as the helicopter is based on concepts and techniques that have been around for a long time and are still experiencing evolutionary advances. The core technologies for electronic hardening are archived in the open literature and the proceedings of international meetings such as the European and U.S. EMC conferences and numerous other conferences dealing with EMI.

LIST OF TECHNOLOGY DATA SHEETS
6.6. HIGH POWER MICROWAVE/RADIO FREQUENCY (HPM/RF)

OFFENSIVE TECHNOLOGIES

High-Power Microwave (HPM) Narrow-Band (NB) Sources

High-Power Microwave (HPM) Wide-Band (WB) Sources

Switching

Pulse Forming Networks (PFNs)

Antennas

The following developing technologies have been identified, but data sheets are not available at this time

OFFENSIVE TECHNOLOGIES

High-Power Microwave (HPM) Narrow-Band (NB) Sources

Hybrid Devices
Increasing Bandwidth
Beam-Plasma Interactions
Pulse Shortening—Tube Design
High Perveance Beams
Multibeam and Sheet Beam Tubes
Amplifier Development
Semiconductor Amplifiers
Frequency Adaptive Sources
Elimination of Electromagnetics

Pulse Compression

Switched Energy Storage
Binary Power Multiplication

Propagation

Absorption and Refraction
Nonlinear Effects
Ground Scattering

DEFENSIVE TECHNOLOGIES

External Electromagnetic (EM) Coupling

Aperture Coupling
External Cable Coupling

Internal Electromagnetic (EM) Coupling

Interior Cable Coupling
Interaction in Complex Systems
Electromagnetic (EM) Re-radiation

Susceptibility and System Response Assessment

Information System Models
Reset of Long-Term Upset
Chaotic Response to High-Power Microwave/Radio Frequency (HPM/RF)

Survivability Assessmen

Trends, Bounds, and Statistics

RF Hardening

Radio Frequency (RF) Absorbers
In-Band Limiters

DATA SHEET 6.6. KLYSTRONS AND RELATIVISTIC KLYSTRONS

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of klystrons and relativistic klystrons are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Current estimates suggest that 10 GW of extracted power may be the limit for a single klystron. One can reasonably expect that 10 klystrons could be phase-locked within the next decade, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of klystron sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Use in RF linear accelerators for tera electron volt (TeV) electron colliders, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Klystrons and relativistic klystrons produce coherent EM radiation in the microwave region by extracting energy from moving electrons. Electrons, which are created at the cathode, do not travel coherently initially. They radiate incoherently and are not capable of exciting EM modes in the microwave cavity structure. By stimulating the source (cathode) electrons with external microwave radiation, electron bunches are formed. These electron bunches then radiate in phase, producing microwave radiation.

Sigurd and Russel Varian invented the first klystron microwave at Stanford University in 1939. Klystrons are the most common source of microwave radiation that uses coherent radiation from bunched electrons. Figure 6.6-5 is a schematic of a two-cavity klystron amplifier.

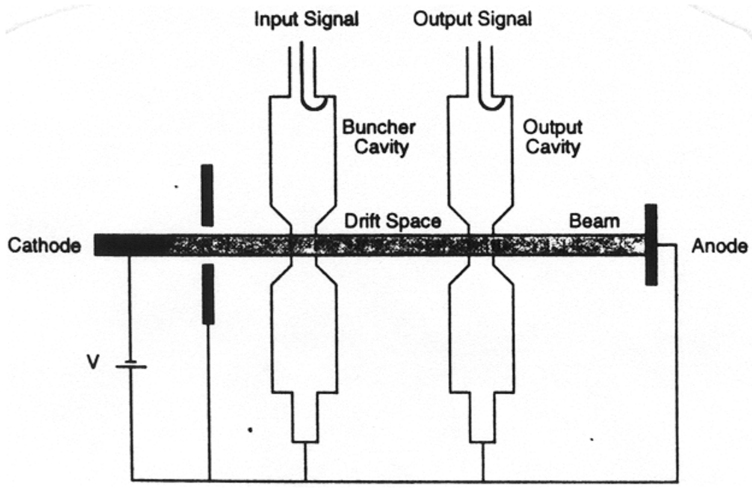


Figure 6.6-5. Schematic of a Two-Cavity Klystron Amplifier (Source: Gold, 1997)

Today's focus is on the two distinct types of RKAs. The first type is a low-current RKA, which is an extension of the basic klystron originally developed for use in linear colliders. This device operates at a perveance of ~ 1 microperv, with an efficiency of about 30 percent. The second type uses a novel electron bunching mechanism. This device operates at a perveance of 10 micropervs, with an efficiency of about 40 percent.

The RKA is a low-impedance source. In some experiments, it has been known to generate peak powers in the 10-GW range, with pulse energies of about 1 kJ. The relationship between peak power, P_p, and operating frequency, f, of the RKA is given by the empirical formula $P_p f = 20$ GW-GHz. This relationship limits the utility of the RKA for the higher frequencies, but it does appear adequate in the 1- to 3-GHz region.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Benford, J.N. et al., *Relativistic Magnetrons and Klystrons at High Repetition Rates and High Average Powers*, Conference Paper, presented at EUROEM '94, Bordeaux, France, June 1994.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development*, Presented at EUROEM '98, Tel Aviv, Israel, 1998.

DATA SHEET 6.6. GAS-FILLED PLASMA TUBES

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. Gas-filled plasma tubes refer to a general class of microwave sources that confine the electron beam by creating a plasma around it. The theoretical limits of performance, such as peak and average power, require definition of the geometry that supports this concept. Fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions in various geometric configurations must also be quantified. Phase-locking gas-filled plasma tubes could greatly enhance the average power, peak power, and energy per pulse.
Critical Materials	Gases that have the right combination of ionization threshold and conductivity to produce stable electron beams.
Unique Test, Production, Inspection Equipment	High-vacuum test beds with high-temperature bake-out capabilities; instrumentation for diagnosing high peak power pulses; pulsed power test equipment for operating at repetition rates greater than 100 Hz.
Unique Software	Computer codes that predict electron beam behavior in gas-filled environments. These codes should be capable of modeling electron plasma interactions, including electron-atom ionization and excitation, conductivity, diffusion, and electron beam instability.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Relativistic electron beams traveling in cylindrical geometry in a vacuum or near vacuum spread radially because of the radial space charge forces. To use the KE of the beam efficiently to generate microwaves, radial spreading must be prevented. One way to accomplish this is to create a plasma by having the energetic electrons of the beam interact with the ambient gas environment.

The interactions of the beam electrons and the ambient gas include ionization, excitation, and scattering. Ionization of the ambient gas produces low-energy electrons, which are repelled from the beam by the radial forces of the electron beam. The removal of the low-energy electrons leaves behind a positive ion presence within the beam, which then reduces greatly the unwanted radial force. The net result is to confine the energetic electron beam better and allow a larger electron beam current to be propagated.

Scattering has a negative effect on the electron beam because it removes the high-energy electrons from the primary direction of travel. Although the ionization increases as the ambient gas pressure increases, so does the scattering. The relative proportion of ionization (desired effect) to scattering (undesired effect) is a function of the electron beam energy, the constituents of the gas, and the geometry. The inclusion of gas filling produces an additional complication in the design of microwave sources that may also enhance the possibility of electrical breakdown.

REFERENCES

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

DATA SHEET 6.6. RELATIVISTIC MAGNETRONS

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of relativistic magnetrons are not well defined. In addition to some fundamental limitations imposed by voltage break-down and the limits of energy transfer between electron in the electron layer and the resonant cavities, the design of the source plays an important role in the efficiency. In a single cavity, 10 GW of extracted power may be the limit. Current estimates suggest that 10 relativistic magnetrons could be phase-locked within the next decade, thereby creating a source with 100 GW of extracted peak power that could be built in the next decade. With an extraction efficiency of 10 percent, a peak power of 100 GW can be achieved. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources could greatly enhance the average power, peak power, and energy per pulse of relativistic magnetrons. Possible fundamental limitations include (1) premature flushing of electrons from the resonant cavity before they deliver a significant fraction of their KE to the EM field and (2) gap closure. If the magnetic field component of the RF field becomes too large, it can temporarily act in opposition to the external magnetic field whose job is to confine the electrons between the cathode and anode. When this happens, the gap collapses, and electrons will strike the anode without producing useful radiated energy.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Relativistic magnetrons are crossed-field devices in which the electrons drift perpendicular to the electric, $\vec{E}$, and magnetic, $\vec{B}$, fields. The drift velocity, $\vec{v}_d$, is given by

$$\vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2} \quad . \tag{1}$$

Arthur Hull invented the magnetron in 1913. George Bekefi and Thaddeus Orzechowski invented the relativistic magnetron in 1975. Figure 6.6-6 shows a basic schematic of the magnetron. The radius to the inner wall of the anode is r_a, and the radius of the cathode is r_c. The external magnetic field is in the axial direction, and the electric field between the anode and cathode is in the radial direction. In this geometry, a layer of electrons is formed and drifts azimuthally around and near the cathode. Because the cavity is a closed structure, a standing wave pattern is established. Microwave radiation is produced by the resonant interactions between the normal modes of the cavity and the natural modes of oscillation of the electron layer. The phase velocity of the EM waves equals the electron drift velocity.

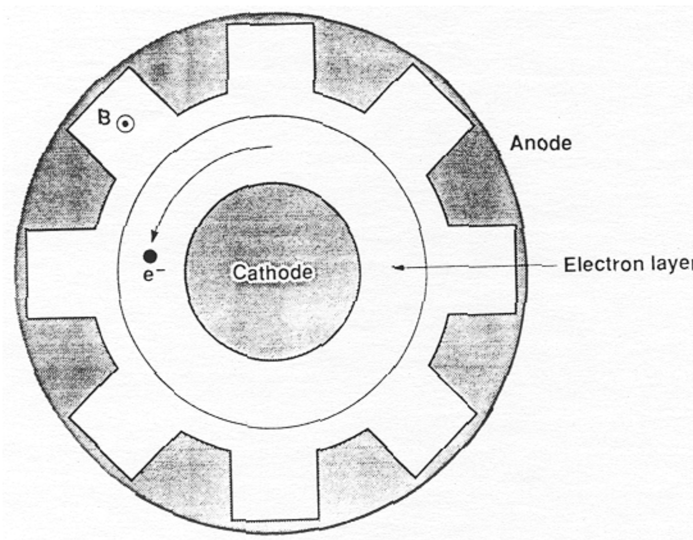


Figure 6.6-6. Schematic of a Magnetron Cavity (Source: Benford and Swegle, 1992)

The configuration of Figure 6.6-6 stays intact as long as the axial magnetic field can prevent the circulating electrons from reaching the anode. In the relativistic limit, the axial magnetic field required to maintain the electron layer, B^* is given by

$$B^* = \frac{2mcr_a}{e(r_a^2 - r_c^2)} \sqrt{\left(\frac{eV}{mc^2} + 1\right)^2 - 1} \quad , \tag{2}$$

where *m* is the electron mass, *c* is the speed of light, *V* is the potential difference between the cathode and anode, and *e* is the electron charge. When the RF produces additional fields that reduce the net field below that given by Eq. (2), electrons will reach the anode, and useful production essentially ceases.

The relativistic magnetron is an extension of the basic magnetron. In contrast to the nonrelativistic basic magnetrons, it employs electrons at relativistic energy and operates at larger currents. These features make the relativistic magnetron a more powerful source than the basic magnetron. Phase-locking several of these devices using an external signal is a major technical challenge.

Table 6.6-3 compares conventional and relativistic magnetrons.

Table 6.6-3. Comparison of Conventional and Relativistic Pulsed Magnetrons (Source: Benford and Swegle, 1992)

Parameter	Conventional	Relativistic
Cathode	Thermionic and secondary emission	Field emission
Voltage	< 100 kV	~ 1 MV
Current	~ 100 A	> 10 kA
Impedance	~ 1000 Ω	~ 100 Ω
Pulse Duration	< 1 μsec	< 100 ns
Power	< 10 MW	> 1 GW
Efficiency	~ 50 percent	< 30 percent

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Benford, J.N. et al., *Relativistic Magnetrons and Klystrons at High Repetition Rates and High Average Powers,* Conference Paper, Presented at EUROEM '94, Bordeaux, France, June 1994.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* Presented at EUROEM '98, Tel Aviv, Israel, 1998.

DATA SHEET 6.6. MAGNETICALLY INSULATED LINE OSCILLATOR (MILO)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of MILOs are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer between the electron layer and the resonant cavity, the design of the source plays an important role in the efficiency. A key feature of MILO is the generation of its own magnetic field. Thus, it does not require an external magnetic field. This makes it more compact and transportable. The geometry and the use of an electron layer instead of an electron beam renders the MILO similar to the relativistic magnetron. It does, however, have a broader bandwidth. In this respect, it could be easier to phase-lock these sources than to phase-lock those of relativistic magnetrons. Another potential advantage of MILO is that the cathode can be made large, reducing the power density and providing a good impedance match to the pulsed power source. MILO is a relatively new device whose largest reported efficiency is less than 5 percent. It must overcome the problem of pulse shortening and increase its efficiency by an order of magnitude to make it a viable candidate for a HPM weapon. The ability to phase-lock these sources would also speed up its feasibility as an HPM weapon.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The principle of MILO is based in large part on the idea of the relativistic magnetron. Figure 6.6-7 shows MILO's geometry. This figure depicts a coaxial geometry, with the inner cylinder being the cathode and the exterior cylinder being the anode. The resonant cavities are located as part of the anode structure. An essential feature of MILO is the absence of an external magnetic field.

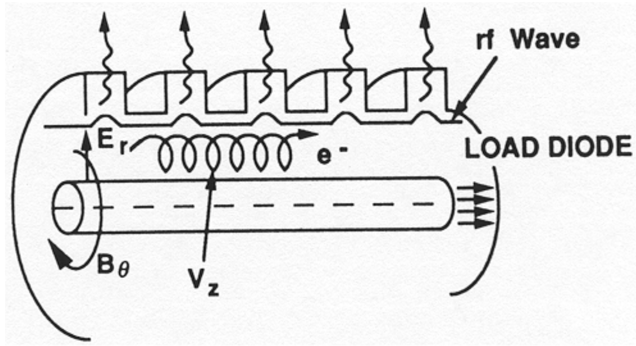


Figure 6.6-7. Geometry of MILO (Source: Benford and Swegle, 1992)

When a large voltage pulse is applied between the anode and cathode, an axial motion of electrons toward the load diode is set up, and this produces an azimuthal magnetic field. This magnetic field insulates the electrons from the anode and creates an electron layer around the cathode. The condition that the electron flow does not reach the anode is given by the requirement that the axial current, I_z, be greater than the parapotential current, I_p. The relevant equations are

$$I_z > I_p = 8500(\ln r_a / r_c)^{-1} \gamma \ln[\gamma + \sqrt{\gamma^2 - 1}] \quad , \tag{1}$$

$$\gamma = 1 + \frac{eV}{mc^2} \quad . \tag{2}$$

In Eq. (2), *m* is the electron mass, *e* is the electron charge, *V* is the cathode to anode voltage, and *c* is the velocity of light.

Like the relativistic magnetron, the electrons in MILO are susceptible to cross-field drift and can arrive at the anode. This is an undesirable effect that erodes the anode structure and can contribute to pulse shortening by plasma generation.

One of MILO's potential advantages is that the cathode can be made large, thus reducing power density and providing a good impedance match to the pulsed power supply.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* Presented at EUROEM '98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. TRAVELING WAVE TUBES (TWTs)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of TWTs are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. The largest reported peak power for a single TWT is less than 400 MW at an efficiency of 45 percent when used as an amplifier. One could reasonably expect this peak power to reach the 1-GW level within the next 10 to 15 years. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of TWT sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

A TWT is an O-type Cerenkov device in which the motion of the electrons is in the direction of the external axial magnetic field. HPM/RF energy transfer from the electrons to the EM field—and, hence, the generation of microwaves—is made possible through use of the periodic structure shown in Figure 6.6-8. The periodic structure leads to mode structures of the EM field that enable energy transfer between the electron beam and the EM field. This energy transfer occurs when the phase velocity of the modes is less than the velocity of light and also approximately equal to the velocity of the electrons.

When electrons travel faster than the phase velocity of the EM wave, a net transfer of energy from the electrons to the EM field occurs, and the electrons are slowed down (they bunch up). The converse is true when the phase velocity is greater than the velocity of the electrons.

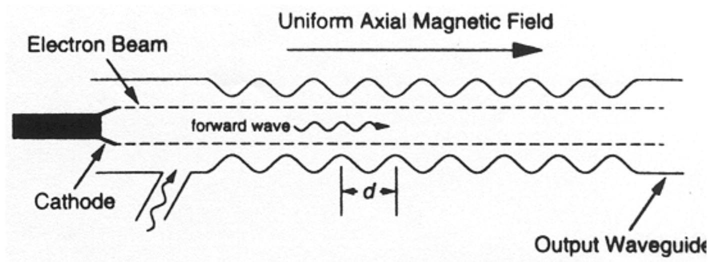


Figure 6.6-8. Schematic of a TWT (Source: Gold, 1997)

The energy in the EM field can travel in both directions—in the direction of the electrons and in the opposite direction. The velocity of energy of propagation is the group velocity (as distinct from the phase velocity) and can take on positive and negative values. These values are predicted from the geometry and characteristics of the electron beam. The case where the group velocity is positive is the TWT. The case where the group velocity is negative is the BWO.

By the choices of geometry, electron beam parameters, and magnetic field, selecting the mode and frequency of operation and generating an NB signal at high power levels is possible. In general, the lowest order modes are the ones that provide the greatest power. This mode selection also determines whether we construct a TWT or a BWO. As shown in Figure 6.6-8, a TWT is constructed since the EM wave and electrons travel in the same direction.

Although TWTs can be operated as an oscillator or as an amplifier, they are inherently more suited to the latter because a strong feedback mechanism does not exist in the structure. Since electrons and the EM wave travel in the same direction, the time available for energy transfer is limited.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases*.

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* Presented at EUROEM '98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. RELTRONS AND SUPER RELTRONS

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of reltrons and super reltrons are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Current estimates suggest that 10 GW of extracted power may be the limit for a single reltron. One can reasonably expect that 10 reltrons could be phase-locked within the next 10 to 15 years, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of reltron sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The super reltron is a device based on the post acceleration of electrons passed through a modulating cavity, such as a split cavity oscillator (SCO). Figure 6.6-9 shows the basic configuration. The SCO-generated modulated beam passes through a relativistic accelerating gap. By bunching the electrons at relativistic energies, the relative energy spread is reduced, and efficiency is improved. The accelerating gap is followed by the output cavities that extract the beam KE.

Reltrons have produced powers of about 500 MW in the 1- to 3-GHz range, with efficiencies approaching 50 percent. Pulses lasting 0.5 to 1 μs have been achieved. In addition, these devices have been mechanically tuned to about 5 percent.

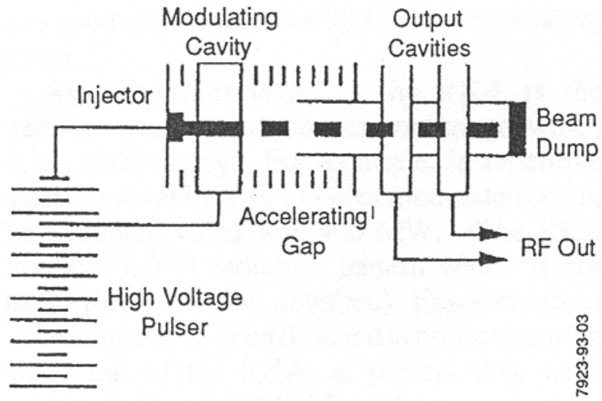


Figure 6.6-9. Schematic of a Super Reltron (Source: Benford, 1993)

Reltrons and super reltrons are compact. The size of these systems, however, may not be small because it is primarily determined by the size of the pulse power system driving them.

REFERENCES

Benford, J. N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J. N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments*, Vol. 68, No. 11, November 1997.

Swegle, J.A., and Benford, J.N., *High-Power Microwaves at 25 Years: The Current State of Development,* Presented at EUROEM '98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. RELATIVISTIC BACKWARD WAVE OSCILLATORS (BWOs)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of relativistic BWOs are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Efficiencies of existing BWOs range between 10 to 45 percent, with peak power levels between 1 and 2 GW. The pulse widths are in the few-nanosecond range. Current estimates suggest that 10 GW of extracted power may be the limit for a single BWO. One can reasonably expect that 10 BWOs could be phase-locked within the next 10 to 15 years, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of BWO sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

A BWO is an O-type Cerenkov device in which the motion of the electrons is in the direction of the external axial magnetic field. HPM/RF energy transfer from the electrons to the EM field—and, hence, the generation of microwaves—is made possible through use of the periodic structure shown in Figure 6.6-10. The periodic structure leads to mode structures of the EM field that enable energy transfer between the electron beam and the EM field. This energy transfer occurs when the phase velocity of the modes is less than the velocity of light and also approximately equal to the velocity of the electrons.

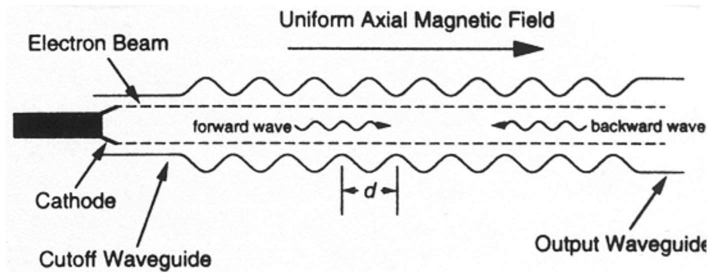


Figure 6.6-10. Schematic of a BWO (Source: Gold, 1997)

When electrons travel faster than the phase velocity of the EM wave, a net transfer of energy from the electrons to the EM field occurs, and the electrons are slowed down (they bunch up). The converse is true when the phase velocity is greater than the velocity of the electrons.

The energy in the EM field can travel in both directions—in the direction of the electrons and in the opposite direction. The velocity of energy of propagation is the group velocity (as distinct from the phase velocity) and can take on positive and negative values. These values are predicted from the geometry and characteristics of the electron beam. The case where the group velocity is positive is the TWT. The case where the group velocity is negative is the BWO.

By the choices of geometry, electron beam parameters, and magnetic field, selecting the mode and frequency of operation and generating an NB signal at high power levels is possible. In general, the lowest order modes are the ones that provide the greatest power. This mode selection also determines whether we construct a TWT or a BWO.

The existence of a backward propagating mode leads to an internal feedback mechanism and makes possible the creation of strong oscillations over a wide range of beam parameters. These oscillations are relatively insensitive to the electron velocity spread. Because of these attributes, the BWO was the first device to generate microwave energy efficiently at high power from relativistic electron beams.

High-efficiency BWOs have been mechanically tuned over a 5-percent bandwidth while operating at constant power.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* presented at EUROEM '98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. MULTIWAVE CERENKOV GENERATOR (MWCG)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of MWCGs are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Current estimates suggest that 10 GW of extracted power may be the limit for a single MWCG. One can reasonably expect that 10 MWCGs could be phase-locked within the next 10 to 15 years, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of MWCG sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The MWCG shown in Figure 6.6-11 uses a slow-wave structure to reduce the axial phase velocity of the microwave radiation below the speed of light. This makes it possible for the electrons to transfer efficiently their KE into microwave EM energy. The MWCG slow-wave structure is divided into a buncher and an output section separated by a drift space. This arrangement maximizes power output and efficiency.

The MWCG has a cross section that is several free-space wavelengths in diameter. This allows several EM modes to exist, and these EM modes can interact simultaneously with the electron beam. The result of this concurrent interaction between the electron beam and the mode is the generation of a signal that is concentrated within a narrow band about a center frequency.

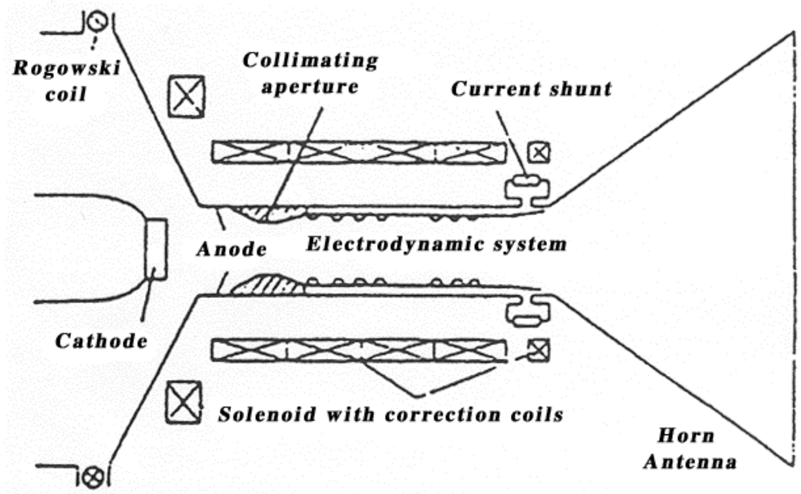


Figure 6.6-11. Schematic of an MWCG (Source: Benford, 1993)

The MWCG devices have held world records for power output. These outputs range from 15 GW at 9.4 GHz to 3 GW at 31 GHz. In some cases, the efficiencies approached 50 percent with pulse lengths in the 60- to 70-ns range. A major limitation of the MWCG is the requirement for extremely large capacitor banks to drive the field coils.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J. N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* presented at EUROEM '98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. RELATIVISTIC DIFFRACTION GENERATOR (RDG)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of RDGs are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Current estimates suggest that 10 GW of extracted power may be the limit for a single RDG. One can reasonably expect that 10 RDGs could be phase-locked within the next 10 to 15 years, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of RDG sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

RDGs are similar to the MWCGs because both are based on the Cerenkov radiation principle. The basic idea is to create a slow-wave structure that reduces the phase velocity of microwave radiation below the speed of light. This makes it possible for the electrons to transfer efficiently their KE into microwave KE.

RDGs are O-type Cerenkov devices—the electron beam travels in the axial direction. Figure 6.6-12 is a basic configuration of an O-type Cerenkov device. The rippled annular structure of the region shown in Figure 6.6-13 produces the EM waves whose phase velocity is less than the speed of light. The diameter of the annular region is at least several free-space wavelengths. This reduces the average power density and increases the amount of power that this device can produce.

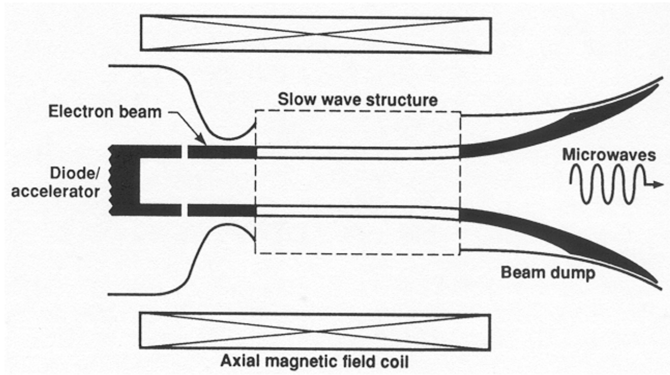


Figure 6.6-12. Basic Configuration of O-type Cerenkov Devices
(Source: Benford and Swegle, 1992)

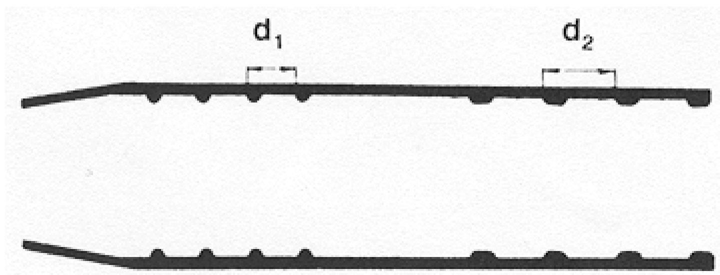


Figure 6.6-13. Schematic of Walls of a Cylindrical Two-Section of an RDG (or an MWDG)
(Source: Benford and Swegle, 1992)

The large diameter of the RDG enables several modes to exist concurrently and makes mode selection difficult. The capability to select a mode is improved using two sections of rippled interior walls, as shown in Figure 6.6-13.

RDGs are capable of producing large amounts of microwave power. RDGs have produced 9 GW of energy at the antenna feed point at 30 GHz and 7 GW of energy at the antenna feed at 45 GHz, with efficiencies of 30 percent. These experiments used electron beams of about 1.5 MeV and about 16 kA of current. Pulse lengths as high as 700 ns were recorded.

REFERENCES

Benford, J.N., *High Power Microwave Generators, Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Benford, J.N. et al., *Relativistic Magnetrons and Klystrons at High Repetition Rates and High Average Powers,* Conference Paper presented at EUROEM ‘94, Bordeaux, France, June 1994.

Gold, S.H., and G.S. Nusinovich, “Review of High-Power Microwave Source Research,” *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* presented at EUROEM ’98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. VIRTUAL CATHODE OSCILLATOR (VIRCATOR)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and for average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of virtual cathode oscillators (vircators) are not well defined. Fundamental limitations in vircator efficiency are attributed to voltage breakdown and poor energy transfer in electron beam-plasma interactions. Vircators typically operate with efficiencies of less than 1 percent, although cases with efficiencies greater than 5 percent have been reported. A vircator has been operated at about 1.5 GW for 30 ns at a frequency of about 2.5 GHz. If efficiency greater than 5 percent for a single virtual cathode oscillator can be consistently achieved, along with the phase-locking of several sources, useful niche applications would be possible. Efficient phase-locking of sources and increasing the pulse length to the 100-ns regime in the peak power mode are key technologies that could enhance greatly the average power, peak power, and energy per pulse of vircator sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Vircators generate microwaves from a relativistic electron beam using a current that exceeds the space-charge-limited current that is inherent in conventional microwave sources. This space-charge-limited current, I_{scl}, is

$$I_{scl} = 8500(\ln r_0 / r_b)^{-1} \gamma \ln[\gamma + \sqrt{\gamma^2 - 1}] \quad , \tag{1}$$

$$\gamma = 1 + \frac{eV}{mc^2} \quad . \tag{2}$$

Figure 6.6-14 shows a schematic of a vircator. The radius of the chamber is r_0, and the radius of the electron beam is r_b. Because the maximum electrostatic energy exceeds the KE of the electrons when the electron current is greater than I_{scl}, a point is reached beyond the anode when the electrons are reflected back toward the cathode. This point, called the virtual cathode, is indicted in Figure 6.6-14. The point in front of the cathode at which reflection occurs is approximately equal to the cathode-to-anode spacing.

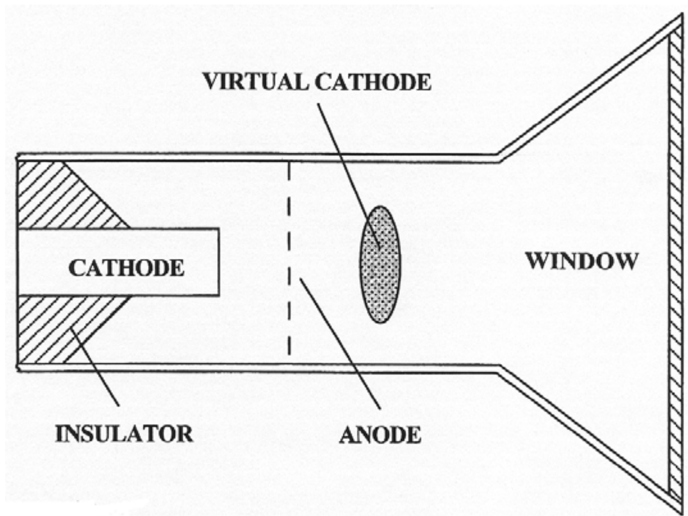


Figure 6.6-14. Schematic of a Virtual Cathode Oscillator (Source: Grothaus, 1997)

In contrast to other NB microwave sources, the geometry of the vircator is quite simple. In particular, it does not require the presence of an external magnetic field. This feature makes it very desirable from an operational viewpoint. Another interesting feature is that the behavior of the vircator is not very sensitive to the details of the cavity structure. Vircators can operate with quality factors (Q) ~ 1–10. These extremely low Q values make the vircator relatively easy to build.

The generation of microwaves from this source derives from the inherent instability of the space charge flow. This instability is manifested in the axial movement of the reflection point, the virtual cathode. The motion is oscillatory in the frequency range below 3 GHz. A certain degree of fluctuation in the oscillation is manifested in a relatively large frequency spread (in comparison with other NB sources) about the center frequency.

Measured efficiencies of vircator are low, rarely exceeding 1 percent. In a few cases, efficiencies exceeding 5 percent have been reached. This appears to be a major limitation of the vircator. Phase-locking two vircators with a few hundred megawatts has been demonstrated.

REFERENCES

Benford, J.N., “High Power Microwave Generators,” *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, “Review of High-Power Microwave Source Research,” *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Grothaus, M.G., “High Power RF Source Technology,” presented at FIESTACROW 97, San Antonio, Texas, April 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* presented at EUROEM ’98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. FREE ELECTRON LASER (FEL)

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of FELs are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Current estimates suggest that 10 GW of extracted power may be the limit for a single FEL. One can reasonably expect that 10 FELs could be phase-locked within the next 10 to 15 years, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of FEL sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

An FEL is a device that generates coherent radiation by the passage of a relativistic beam through a periodic "wiggler field." Figure 6.6-15 shows the FEL geometry. The alternating polarity of the magnetic field produces the wiggle. This magnetic field configuration has demonstrated that coherent radiation can be generated not only in the microwave band, but also up to frequencies in the UV region. The ability of the FEL to produce coherent EM radiation over such a wide frequency range is what distinguishes this device from other HPM sources.

The efficiency of FEL experiments conducted in the 1960s was typically under 1 percent—caused by using electron beams with very large velocity spreads. By the 1970s and 1980s, the efficiencies improved to about 5 percent. Peak power levels greater than 1 GW were produced at 35 GHz, with a 20-ns pulse.

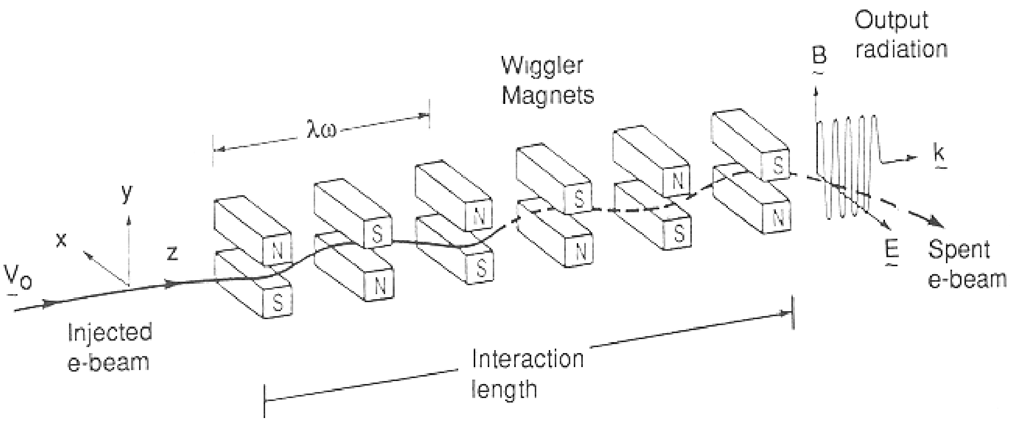


Figure 6.6-15. The Basic FEL Configuration (Source: Benford and Swegle, 1992)

The key parameters for an FEL microwave source are the efficiency of electron beam energy to microwave energy and the bandwidth over which the signal is amplified. The initial spread of the electron beam that enters into the wiggler is a major factor in the conversion of electron beam energy into microwave energy. Spreads in electron beam energy remove some of the electrons from the resonance condition and reduce the efficiency. In some cases, the efficiency could be an order of magnitude, with only a 1-percent spread in axial velocity.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments*, Vol. 68, No. 11, November 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development*, presented at EUROEM '98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. GYRODEVICES

Developing Critical Technology Parameter	For military systems, the frequency range of interest is nominally between 500 MHz and 100 GHz. Many military targets have enhanced susceptibility between 1 and 3 GHz. The critical technical parameters are different for peak power considerations and average power considerations. Peak power requirements at a nominal frequency of 1 GHz are as follows: peak power is greater than or equal to 1 GW, source efficiency is greater than 50 percent, energy per pulse is greater than or equal to 300 J, pulse duration is greater than or equal to 500 ns, pulse repetition rate is greater than or equal 100 Hz, burst duration is greater than or equal to 1 sec (100 pulses), and on-target power density at a range of 1 km is greater than 100 W/cm^2. Average power requirements at a nominal frequency of 1 GHz are as follows: minimum average power is 30 kW, maximum average power is greater than 1 MW, source efficiency is greater than 50 percent, duty cycle is greater than 10^{-4}, and on-target power density at a range of 1 km is from 0.1 to 1.0 W/cm^2. The theoretical limits of peak and/or average power of gyrodevices are not well defined. In addition to some fundamental limitations imposed by voltage breakdown and the limits of energy transfer in electron beam-plasma interactions, the design of the source plays an important role in the efficiency. Current estimates suggest that 10 GW of extracted power may be the limit for a single gyrodevice. One can reasonably expect that 10 gyrodevices could be phase-locked within the next 10 to 15 years, thereby creating a source with 100 GW of extracted peak power. If the pulse length can be maintained as the peak power grows from the current level to 100 GW, a peak energy per pulse of 10 kJ is possible. Efficient phase-locking of sources is a key technology that could enhance greatly the average power, peak power, and energy per pulse of gyro-device sources.
Critical Materials	Chemicals that provide clean surfaces for use in high-electric field applications; cathode materials that sustain high current densities and low gap closure rates; cathodes whose emitted materials have high atomic numbers.
Unique Test, Production, Inspection Equipment	Electrical and chemical processes and procedures that provide clean surfaces for use in high-electric field applications.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications, environmental cleanup, and industrial processes.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Gyrodevices refer to a family of devices that generate microwaves by extracting the rotational energy of electrons in a magnetic field. These devices include gyromonotrons, gyroklystrons, gyro-TWTs, gyro-BWOs, gyrotwystrons, and quasi-optical gyrotrons. These devices are relatively simple. The basic requirement is to have a suitably large component of electron velocity that is perpendicular to the magnetic field. Figure 6.6-16 is a schematic of the gyrotron, one of the most popular gyrodevices.

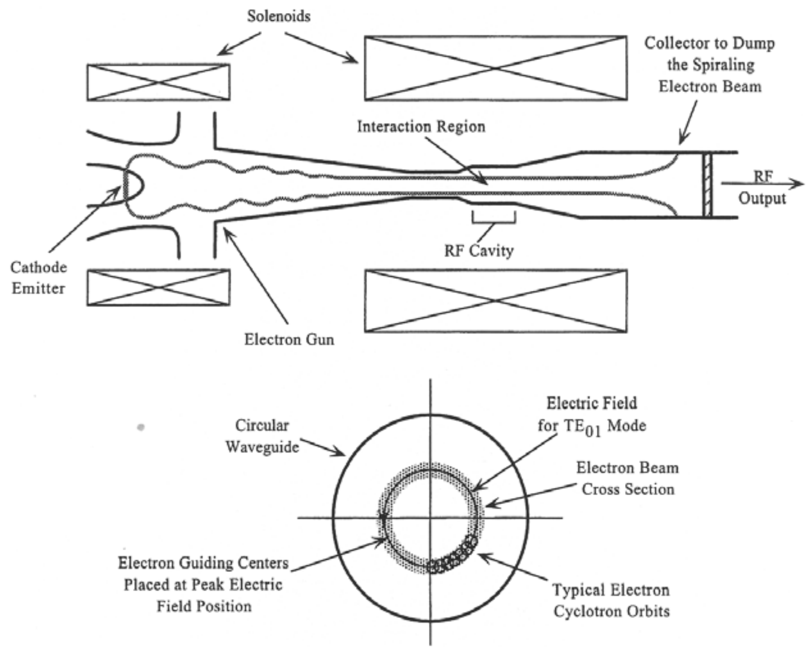


Figure 6.6-16. Schematic of a Gyrotron (Sources: Benford and Swegle, 1992, and Grothaus, 1997)

The top half of Figure 6.6-16 allows one to glean much of the basic physics of gyrodevices. The electron gun generates the electron that goes into the RF cavity. The axial magnetic field has a peak value in the region of the large solenoid. A key parameter of this system is the ratio of the beam electron’s perpendicular velocity to its axial velocity.

The bottom half of Figure 6.6-16 shows the rotational electron motion within the circular waveguide. OF particular interest is the annular cross section of the electron beam, whose minimum value is the Larmor radius—the electron perpendicular velocity divided by the cyclotron frequency.

The interaction of the electron beam with the various cavity EM transverse electric (TE) and transverse magnetic (TM) modes determines the frequency of operation.

REFERENCES

Benford, J.N., “High Power Microwave Generators,” *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc. Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, “Review of High-Power Microwave Source Research,” *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

Grothaus, M.G., *High Power RF Source Technology*, presented at FIESTACROW 97, San Antonio, TX, April 1997.

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development*, presented at EUROEM ’98, Tel Aviv, Israel 1998.

DATA SHEET 6.6. PHASE-LOCKING

Developing Critical Technology Parameter	Phase stability of ±3 degrees using injected signals less than 0.5 percent of the output.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Developing lethal levels of EM energy on target may require effective radiated power levels that exceed the capability of an individual source. The limit on any source is set by air breakdown at the antenna. By phase-locking sources, a coherent wave front on the target is produced. When the timing is accurate, the resulting on-target power is substantially greater than that produced by a single source.

Techniques for phase-locking depend on the type of source. For example, phase-locking of magnetrons is different from phase-locking of klystrons. Phase-locking of seven magnetrons has been demonstrated.

REFERENCES

Benford, J. N. and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Benford, J.N. et al., "Relativistic Magnetrons and Klystrons at High Repetition Rates and High Average Powers," Conference Paper, presented at EUROEM '94, Bordeaux, France, June 1994

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Swegle, J.A., and J.N. Benford, *High-Power Microwaves at 25 Years: The Current State of Development,* presented at EUROEM '98, Tel Aviv, Israel, 1998.

DATA SHEET 6.6. CATHODES

Developing Critical Technology Parameter	"Cold" cathodes that work at modest vacuum, provide suitable current densities, have useful lifetime, and a brightness greater than 10^{11} A/m^{2}rad^2.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	High-vacuum test beds with high-temperature bake-out capabilities; instrumentation for diagnosing high peak power pulses; pulsed power test equipment for operating at repetition rates greater than 100 Hz.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

All high-power CW and repetitive microwave devices require a large high-energy electron beam current. The source of these electrons is a cathode. The most common type of cathode is based on thermionic emission. The electrons are extracted from the cathode in a Pierce geometry that is surrounded by focusing electrodes. Focusing the electron beam is made easier as the electron beam diameter is made smaller. Hence, a figure of merit for a cathode is its maximum current density since this will reduce the beam diameter for a fixed required total current.

Figure 6.6-17 compares cathode brightness as a function of total current for different cathode emitters. The Massachusetts Institute of Technology (MIT) velvet and graphite points apply to field-emission cathodes. The Naval Research Laboratory (NRL) and Los Alamos National Laboratory (LANL) points refer to thermionic-emission cathodes, and the remaining two points apply to photoemission.

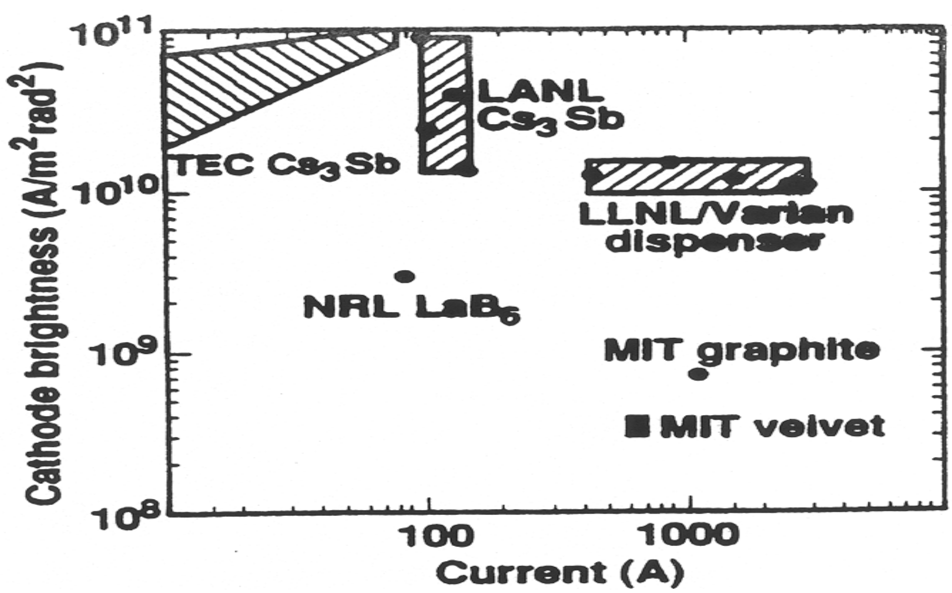


Figure 6.6-17. Cathode Brightness as a Function of Current (Source: Benford and Swegle, 1992)

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments*, Vol. 68, No. 11, November 1997.

Grothaus, M.G., "High Power RF Source Technology," presented at FIESTACROW 97, San Antonio, TX, April 1997.

DATA SHEET 6.6. MODE CONTROL/MODE CONVERSION

Developing Critical Technology Parameter	Single propagation mode.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Being able to operate in a single mode is a critical issue in all high-power microwave sources. The physical dimensions of these sources allows many TE and TM modes to exist. Moreover, these modes can be amplified from the EM fluctuations arising from the electron beam.

REFERENCES

Benford, J.N., "High Power Microwave Generators," *Proceedings of the 1993 International Conference on Plasmas and Ionized Gases.*

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments,* Vol. 68, No. 11, November 1997.

DATA SHEET 6.6. MICROWAVE WINDOWS

Developing Critical Technology Parameter	Transmission factors greater than 90 percent at breakdown fields greater than 1 MV/m.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The ideal microwave window would allow the passage of microwave radiation without any loss or dispersion. It would also resist being impaired by the large electric fields that exist at the triple point—where the air, metallic structure, and window meet. This is fundamentally a materials problem.

The desired material should be strong enough to resist the mechanical stresses created by the electric field. It should also be resistant to field emission since this could create undesired ionization in the local region and facilitate undesired air breakdown.

REFERENCES

Benford, J. N. and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

DATA SHEET 6.6. MODULATION TECHNIQUES

Developing Critical Technology Parameter	Modulation techniques that can generate duty cycles greater than 10 percent and operate in the frequency range between 0.4 and 100 GHz. These modulated sources should produce a peak power greater than or equal to 1 GW, an energy per pulse greater than or equal to 300 J, a pulse duration greater than or equal to 500 ns, and a pulse repetition rates greater than or equal 100 Hz, with a burst duration greater than or equal to 1 s.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	High-vacuum test beds with high-temperature bake-out capabilities; instrumentation for diagnosing high peak power pulses; pulsed power test equipment for operating at repetition rates greater than 100 Hz.
Unique Software	None identified.
Major Commercial Applications	Uses include medical surgical applications.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Tailoring a microwave pulse to a particular shape is accomplished via power conditioning. When applied to high-duty-factor microwave systems, the power conditioning systems are called modulators. A typical modulator consists of several subsystems connected in sequence. This modulator transforms the energy from a primary high-voltage source to the desired pulse voltage source that creates the high-energy and high-current electron beam.

A key component of the modulator is the PFN (pulse forming network). The PFN consists of capacitors, inductors, and switches that produce the desired pulse waveform to the step-up transformer. This transformer generates the Mega-volt-range output that produces relativistic high-current electron beams that drive the microwave sources.

REFERENCES

Benford, J. N. and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments*, Vol. 68, No. 11, November 1997.

DATA SHEET 6.6. PULSE SHORTENING

Developing Critical Technology Parameter	The critical technology parameter is the microwave pulse length. Any level of improvement is desired. A pulse length greater than 100 ns is a significant milestone for achieving lethality.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Medical applications.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Pulse shortening is an extremely important issue in developing a useful NB source. This term describes several physical processes that limit the time duration of a pulse in NB HPM sources. More specifically, it refers to the situation where microwaves cease being generated in a source before the pulsed power source stops. The five major causes of pulse shortening are plasma generation, electron streaming, high electric fields, beam dispersion, and inefficient tube design. Pulse shortening is a serious problem that must be overcome if the energy levels per pulse are to reach the desired levels for lethality, roughly in the kilojoule range.

As electron beams are created on the surface of an explosive emission diode, plasma is concurrently created at the diode surface. This plasma is capable of back streaming, expanding into the transmission line feeding the diode. Since the plasma is a good conductor, the diode shorts out. Electron streaming refers to situations where electrons travel to structures in which they do not belong. An example of electron streaming is electrons that move away from the accelerating gap, causing diode impedance degradation.

Breakdown at walls created by high electric fields produces local discharges. These discharges are high conductive paths that can cause the HPM tube to turn off. Controlling wall breakdown is connected with the overall problem of tube design. If an HPM tube is not properly designed, it can also enhance the possibility of beam-plasma instabilities. These instabilities interrupt the electron beam—another cause of pulse shortening.

REFERENCES

Agee, F.J., "Evolution of Pulse Shortening in Narrow Band, High Power Microwave Sources," *IEEE Trans. Plasma. Sci.*, Vol. 26, No. 3, pp. 235–245, June 1998.

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Gold, S.H., and G.S. Nusinovich, "Review of High-Power Microwave Source Research," *Review of Scientific Instruments*, Vol. 68, No. 11, November 1997.

Price, D., and J.N. Benford, "General Scaling of Pulse shortening in Explosive-Emission-Driven Microwave Sources," *IEEE Trans. Plasma. Sci.*, Vol. 26, No. 3, pp. 256–262, June 1998.

Price, D., J.S. Levine, and J.N. Benford, "Diode Plasma Effects on the Microwave Pulse Length From Relativistic Magnetrons," *IEEE Trans. Plasma. Sci.*, Vol. 26, No. 3, pp. 348–353, June 1998.

DATA SHEET 6.6. SPARK GAPS FOR WIDE-BAND (WB) SOURCES

Developing Critical Technology Parameter	For WB sources, spark gaps operate as peaking switches. The spark gap routinely and reliably has to generate voltages above hundreds of kilovolts with risetimes less than 1 ns and preferably less than 0.1 ns. To maintain risetimes in the subnanosecond range, the inductance of the spark gap has to be less than 1 nH. This, in turn, requires a gap spacing of less than 1 mm. Pulse repetition rates greater than 1 kHz are also required. A repetition rate of 10 kHz is a near-to-moderate-term goal.
Critical Materials	The combination of voltages in the hundreds of kilovolt regime and gap spacing less than 1 mm leads to electric fields in the Megavolt-per-centimeter range. Spark gap materials that can operate in the Megavolt-per-centimeter range for hundreds of thousands of pulses in the subnanosecond range are required for operational use. For gas switches, such as hydrogen, these materials must operate in the 100-atm (1,400 psi) range. Spark gap materials must also be chemically compatible with the oil used in oil switches.
Unique Test, Production, Inspection Equipment	Fabrication techniques that will allow an electric field of the order of 100 MV/m to be maintained around electrodes without premature discharging.
Unique Software	None identified.
Major Commercial Applications	Automotive; radar; sensors.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region. Jamming and spoofing are also likely uses for WB systems at very high repetition rates.

Pulsed power sources for WB waveforms can be conceptually simple. The main ingredients consist of a switch coupled to the transmitting antenna. The key technologies for WB weapons are fast switches and antenna design. Spark gaps provide a relatively simply means of switching large amounts of microwave energy in the nanosecond regime. The inherent simplicity of the device facilitates the development of compact NB sources.

Spark gap technology has been around for a long time. Figure 6.6-18 shows a schematic of a spark gap used in WB sources. The small radius of the spark channel, r_i, produces a high inductance, L_s. This may result in a slower-than-desired risetime. Another factor that limits the risetime of the pulse is the transit time for the EM wave to travel from one electrode to the other after the breakdown process has been initiated. The transit time between the electrodes can be reduced by correspondingly making the inter-electrode gap distance smaller. However, when this is done, the voltage required for breakdown is reduced, which ultimately reduces the radiated power.

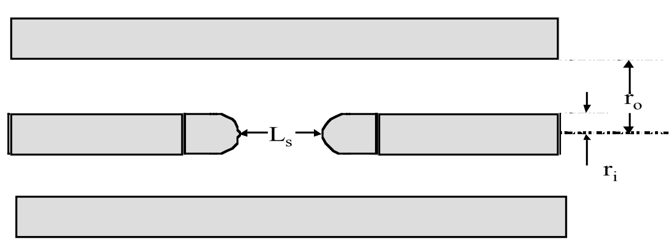


Figure 6.6-18. Schematic of a Spark Gap Used in WB (Source: Lehr et al., 1998)

REFERENCES

Lehr, J.M., C.E. Baum, W.D. Prather, and R.J. Torres, “Fundamental Physical Considerations for Ultrafast Spark Gap Switching,” in *Ultra Wideband Short Pulse Electromagnetics 4*, E. Heyman et al. (Eds.), Plenum Press, 1998.

Prather, W.D., C.E. Baum, F.J. Agee, J.P. O’Laughlin, D.W. Scholfield, J.W. Burger, J. Hull, J.S.H. Schoenberg, and R. Copeland, “Ultra Wideband Sources and Antennas,” in *Ultra Wideband/Short Pulse Electromagnetics 4*, E. Heyman et al. (Eds.), Plenum Press, 1998.

DATA SHEET 6.6. SOLID-STATE SEMICONDUCTOR SWITCHES

Developing Critical Technology Parameter	Semiconductor-based avalanche switches that have a risetime less than 100 ps, an adjustable pulse width up to 5 ns, and a rms jitter of less than 10 ps. These switches should be able to be stacked to provide a net output voltage of more than 50 kV.
Critical Materials	High-purity, low-cost silicon (Si); silicon carbide (SiC).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Conventional radar; impulse radar; material-penetrating radar.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region. Jamming and spoofing are also likely uses for WB systems at very high repetition rates.

Pulsed power sources for WB waveforms can be conceptually simple. The main ingredients consist of a switch coupled to the transmitting antenna. The key technologies for WB weapons are fast switches and antenna design. Semiconductor-based stacked avalanche switches provide a reliable means of switching large amounts of microwave energy in the nanosecond regime. These devices also permit flexibility in pulse width, which can also increase the lethality of the source. Another advantage of semiconductor avalanche switches is that a laser is not required for triggering.

Laser-controlled photoconductive solid-state switching (PCSS) is a means of generating the impulse-like waveforms required for WB applications. Switches based on this technology are expensive. Lifetime limitations are also imposed by filamentation and contact degradation. Alternative methods of solid-state switching that do not require lasers to achieve ultralow jitter triggering are desired.

An alternative approach to achieving ultralow jitter developed by Frost and Focia uses miniature triggered solid-state switched pulsers based on the delayed breakdown effect. I.V. Grekhov and A.F. Kando-Sysoev of the Ioffe Institute in St. Petersburg, Russia, discovered this effect in 1979. These researchers showed that when a delayed breakdown device (DBD) made of Si (see Figure 6.6-19) is rapidly overvolted beyond static breakdown, a delay of several nanoseconds occurs before breakdown. Figure 6.6-19 demonstrates the concept. Picosecond breakdown is produced when ionization sweeps across the n-region (center section) faster than the carrier drift velocity.

Working on the delay breakdown principal, Frost and Focia demonstrated that a multistage series of EM shock line pulsers employing DBD devices could produce high-velocity fast risetime pulsers with very low jitter. The jitter level is low enough to allow the development of arrays of impulse sources. Another important achievement is the ability to use SiC instead of Si. The advantages of SiC are higher stand-off voltage, higher thermal conductivity, and operation at higher temperatures.

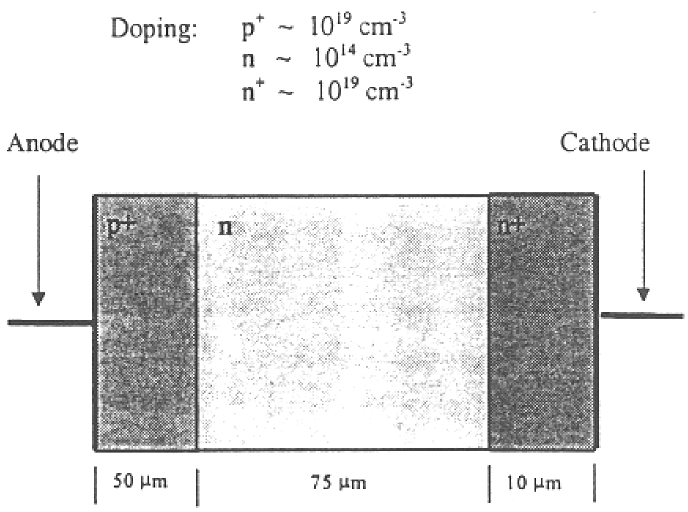


Figure 6.6-19. DBD Structure (Source: Frost and Focia)

REFERENCES

Frost, C.A., and R.J. Focia, "*Solid State Switched Array Impulse Source*," Pulse Power Physics, Inc., published as Air Force Research Laboratory Report (AFRL–DE–TR–1999–1041), March, 1999.

Grekhov, I.V., and A.F. Kando-Sysoev, "Subnanosecond Current Drops in Delayed Breakdown of Silicon p-n Junctions," *Sov. Tech. Phys. Lett. 5* (8), 395, 1979.

Prather, W.D., C.E. Baum, F.J. Agee, J.P. O'Laughlin, D.W. Scholfield, J.W. Burger, J. Hull, J.S.H. Schoenberg, and R. Copeland, "*Ultra Wideband Sources and Antennas*," in *Ultra Wideband/Short Pulse Electromagnetics 4*, E. Heyman et al. (Eds.), Plenum Press, 1998.

DATA SHEET 6.6. SOLID-STATE PHOTOCONDUCTIVE SWITCHES

Developing Critical Technology Parameter	Photoconductive solid-state switches with risetimes less than 100 ps, less than 10 ps rms jitter, and greater than 3×10^9 shot lifetime. The ability to achieve reliably a pulse repetition frequency greater than 10 kHz and peak power in the hundreds-of-Megawatt regime would increase the applicability of this technology.
Critical Materials	High purity gallium arsenide (GaAs).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Conventional radar; phased array radar; impulse radar.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region. Jamming and spoofing are also likely uses for WB systems at very high repetition rates.

Pulsed power sources for WB waveforms can be conceptually simple. The main ingredients consist of a switch coupled to the transmitting antenna. The key technologies for WB weapons are fast switches and antenna design. PCSS switching provides the potential for very low turn-on jitter, fast risetime (and wide bandwidth), small volume, and phasing of modules.

A major advance in PCSS occurred in the late 1980s with the discovery that a GaAs fast recovery switch would remain conducting even after the optical triggering pulse was turned off and that the switch risetime was not limited by the laser risetime. The time scale for this phenomenon was shown to be applicable to the generation of WB microwave sources.

Two notable examples of PCSS switches developed under joint government programs are the bistable optically controlled semiconductor switch (BOSS) shown in Figure 6.6-20, and the bulk avalanche semiconductor switch (BASS) shown in Figure 6.6-21.

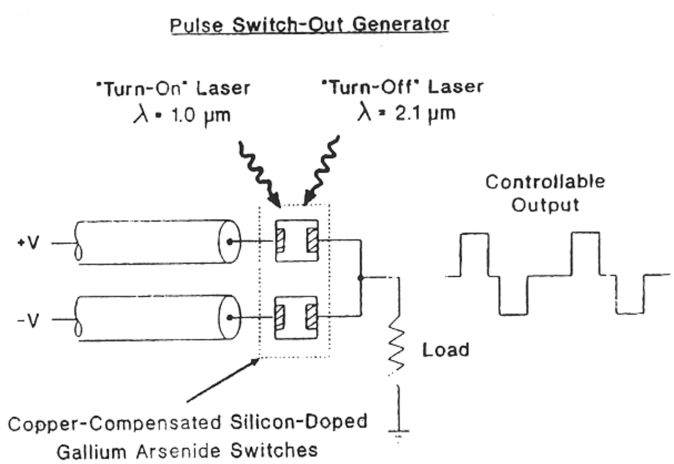


Figure 6.6-20. Bistable Optically Controlled Semiconductor Switch (BOSS) (Source: Stoudt, 1995)

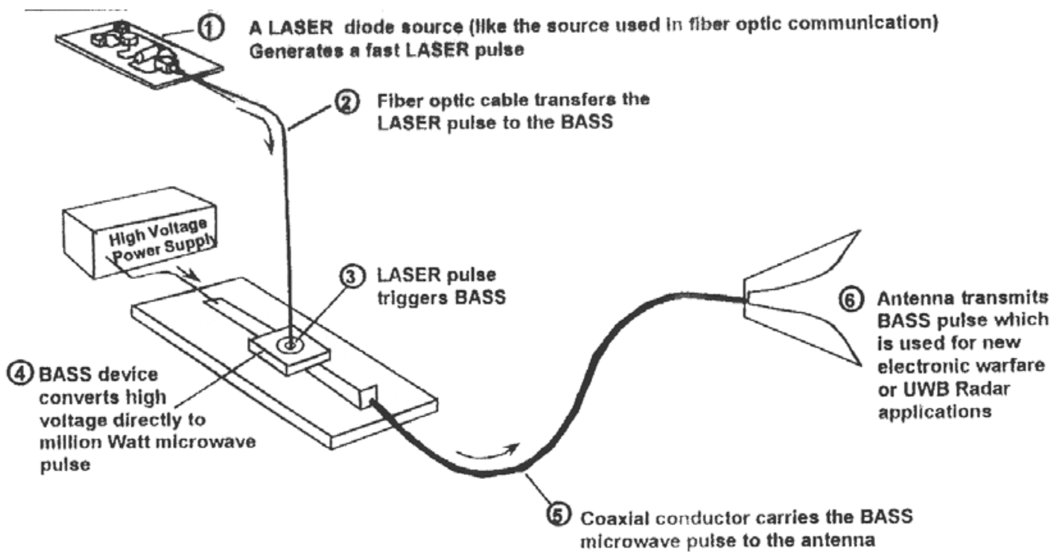


Figure 6.6-21. Bulk Avalanche Semiconductor Switch (BASS)
(Source: Oicles, Staskus, and Brunemeier, 1995)

The BOSS switch is operated in the linear mode, not the avalanche mode. In this mode, the conductivity is proportional to the intensity of the laser light. Although fast switching is possible using this technology, experiments to date have shown that this technology does not scale at powers required for current applications.

The BASS is a fast risetime GaAs semiconductor switch that operates around 10 kV. These switches become conductive at a selected wavelength and then fire in an avalanche mode. The power requirements for the initiation of the avalanche are low. A very small amount of light generated by a laser diode and carried by a fiber-optic link is sufficient. The modest power requirements for initiation allows flexibility in the placement of BASS switches and the design of individually controlled elements. Oicles, Staskus, and Brunemeier have demonstrated antenna arrays based on the BASS principle.

REFERENCES

Oicles, J., M. Staskus, and P. Brunemeier, "High-Power Impulse Generators for UWB Applications," *Ultra Wideband/Short Pulse Electromagnetics 2*, L. Carin and L.B. Felsen (Eds.), Plenum Press, New York, 1995.

Prather, W.D., C.E. Baum, F.J. Agee, J.P. O'Laughlin, D.W. Scholfield, J.W. Burger, J. Hull, J.S.H. Schoenberg, and R. Copeland, "Ultra Wideband Sources and Antennas," *Ultra Wideband/Short Pulse Electromagnetics 4*, E. Heyman et al. (Eds.), Plenum Press, 1998.

Stoudt, D.C., "Demonstration of Frequency-Agile RF Source Configuration Using Bistable Optically Controlled Semiconductor Switches," *IEEE International Pulse Power Conference*, 1995.

DATA SHEET 6.6. SOLID-STATE LATERAL SWITCHES

Developing Critical Technology Parameter	Lateral solid-state switches with closure times less than 300 to 430 ps, less than 10 ps rms jitter, greater than 2×10^6 shot lifetime, and greater than 135 kV hold-off voltage across a 1.0-cm gap. The ability to achieve reliably a pulse repetition frequency greater than 10 kHz and peak power in the hundreds-of-Megawatt regime would increase the applicability of this technology.
Critical Materials	High-purity GaAs.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Conventional radar; phased array radar; impulse radar.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region. Jamming and spoofing are also likely uses for WB systems at very high repetition rates.

Pulsed power sources for WB waveforms can be conceptually simple. The main ingredients consist of a switch coupled to the transmitting antenna. The key technologies for WB weapons are fast switches and antenna design. Solid-state lateral switches provide the potential for very low turn-on jitter, fast risetime (and wide bandwidth), small volume, and phasing of modules.

Lateral PCSS technology uses GaAs wafers. In contrast to bulk avalanche solid-state switches, the current on these wafers is conducted along an undoped GaAs surface gap between two specially shaped contacts. These switches can operate at much higher voltages than those based on bulk avalanche technology. Currently, these switches can operate in the 50- to 130-kV region. They have been incorporated into switched transmission lines and Blumleins connected to WB transmission electron microscopy (TEM) horns. Since lateral PCSS switches are initiated optically, they can be incorporated in an array to increase the radiated power significantly.

REFERENCES

Prather, W.D. et al., *Ultrawide Band Sources and Antennas: Present Technology, Future Challenges,* presented at AMEREM Conference, Albuquerque, NM, 1996.

Prather, W.D. et al., “Ultra-Wideband Source and Antenna Research,” *IEEE Trans on Plasma Science, Special Issue on HPM,* 2000 (in press).

DATA SHEET 6.6. TRIGGERED GAS SWITCHES

Developing Critical Technology Parameter	Reduction of jitter to less than 65 ps using a charge voltage of 2.5 kV with a 500-ps risetime.
Critical Materials	Hydrogen; nitrogen; tungsten.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Conventional radar; phased array radar; impulse radar.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region. Jamming and spoofing are also likely uses for WB systems at very high repetition rates.

Pulsed power sources for WB waveforms can be conceptually simple. The main ingredients consist of a switch coupled to the transmitting antenna. The key technologies for WB weapons are fast switches and antenna design. Triggered gas switches provide the potential for very low turn-on jitter, fast risetime (and wide bandwidth), small volume, and phasing of modules. Further exploitation of WB microwave weapons may be possible using field enhanced triggers or laser triggers into high pressure hydrogen switches that already have high repetition rates and fast risetimes.

REFERENCES

Prather, W.D. et al., *Ultrawide Band Sources and Antennas: Present Technology, Future Challenges,* presented at AMEREM Conference, Albuquerque, NM, 1996.

Prather, W.D. et al., "Ultra-Wideband Source and Antenna Research," *IEEE Trans on Plasma Science, Special Issue on HPM,* 2000 (in press).

DATA SHEET 6.6. WIDE-BAND (WB) SYSTEMS

Developing Critical Technology Parameter	This technology pertains to the development of techniques and devices for integrating the components of a WB system into reliable and transportable units that can be fielded as weapons. Any level of technical innovation is important. Of particular interest are those technologies that reduce weight and/or volume, make the systems more reliable, and enable operation at high altitudes.
Critical Materials	SF_6; gas insulating materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Transportable impulse radar.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region. Jamming and spoofing are also likely uses for WB systems at very high repetition rates.

There are many practical situations in which a transportable WB system is useful. Figure 6.6-22 shows such a configuration.

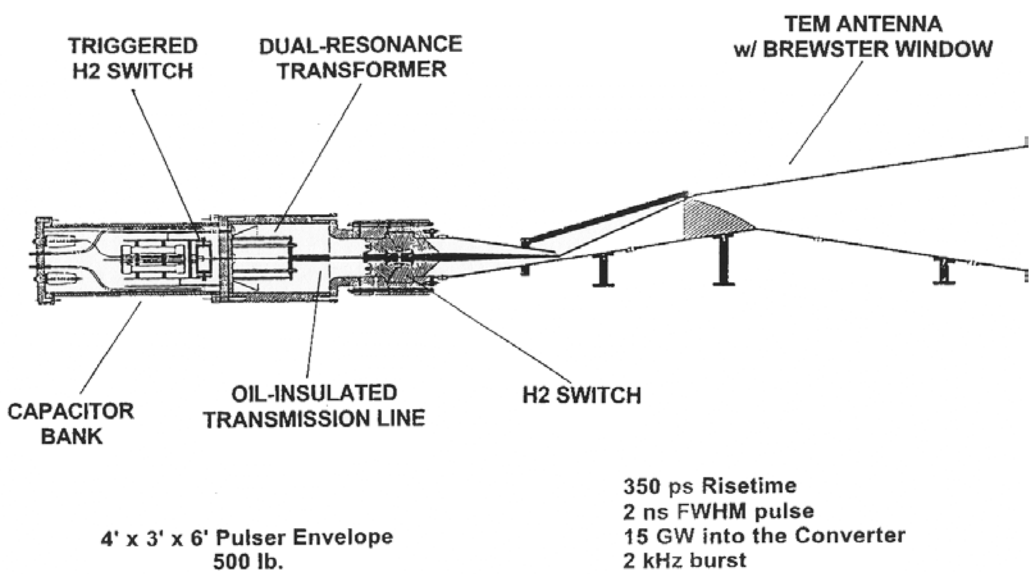


Figure 6.6-22. Fieldable High-Power WB System (Source: Copeland)

REFERENCES

Copeland, R., High Power Microwave Conference, 1997.

DATA SHEET 6.6. DIAMOND SEMICONDUCTOR SWITCHES

Developing Critical Technology Parameter	Each switch should have the following capabilities: operation at average power levels greater than 100 kW, duty cycles greater than or equal to 0.01, peak current density in pulsed mode greater than 100,000 A/cm^2, voltages greater than 100 kV, risetimes less than 1 ns, and internal inductance less than 1 nH per ampere. When used in PFNs for NB HPM, diamond semiconductor switches are required to deliver at least 1 MJ per pulse. Nuclear radiation hardness is also a requirement for operation in a nuclear environment.
Critical Materials	These switches and related contacts and leads must be capable of operating at high temperatures because of the intrinsic energy dissipation inherent in switches. This would suggest materials that have high specific heat and high conductivity.
Unique Test, Production, Inspection Equipment	Equipment that can fabricate a system of switches that provide the required synchronism better than 1 ns for parallel operation.
Unique Software	Software that can support the fabrication process.
Major Commercial Applications	So far, the only applications for this technology have been military. Potential commercial opportunities include applications in electric power, the automotive industry, and electric drives.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Fast switching could be used to generate short risetime pulses to antennas for WB application and can be used to improve phase-locking of NB sources. Development of faster switches will lead to higher repetition rates and an increase in the bandwidth. Diamond semiconductor switches show promise for meeting the requirements.

Diamond semiconductor switches may have the capability to meet the demanding high-power handling requirements for HPM applications. Diamond is chemically inert, has high thermal conductivity, and can produce copious amounts of electrons under relatively low values of electrical field. The breakdown voltage and the current handling capacity of a switch are the principal parameters that determine the suitability of high-power switches for this application. Diamond semiconductor switches appear to have the capability to operate in the 10-kV range, with about 5 kA. A key requirement in achieving these goals is the development of high-quality diamond film.

DATA SHEET 6.6. CAPACITORS

Developing Critical Technology Parameter	Dielectric materials capable of storing more than 10 kJ/kg. These materials must operate at the high power levels required for HPM weapons applications and must be capable of transferring stored electrostatic energy to the PFN in less than 1 μs (for some applications). Probability of failure during discharge should be consistent with military requirements.
Critical Materials	Polymers; ceramics; electrolytes; diamonds; glass-ceramic composites; and so forth.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	There appears to be little commercial interest in developing capacitors for HPM applications. Commercial applications include high-power flash lamps, motor starter circuits, and so forth.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

Capacitors that can meet the power density, total energy, and energy discharge rates for HPM/RF applications and can be incorporated into PFNs are good candidate for incorporation in mobile airborne and land-based platforms.

The principle of using capacitors as energy storage devices is an old technology. The maximum energy stored per unit volume, $U_{\max}$, is given by

$$U_{\max} = \frac{1}{2}\varepsilon E^2 \quad ,$$

where E is the breakdown electric field and ε is the permittivity. These parameters are intrinsic material properties of the dielectric.

There is always continuing interest, at some level, in developing capacitors that can operate at higher voltage and higher energy density. Increasing the breakdown field will allow higher voltages to be achieved with smaller physical dimensions. For application to HPMs, capacitors must also be able to discharge their energy rapidly, with low inductance and minimum energy loss per discharge. These goals can be met more easily by increasing the energy storage per unit volume.

DATA SHEET 6.6. INTERMEDIATE-ENERGY-STORAGE FLYWHEELS

Developing Critical Technology Parameter	High-frequency pulsed generators that can deliver pulses faster than a millisecond; achieving acceptable vibration levels that are consistent with the strength of materials; increasing the number of cycles to failure.
Critical Materials	Insulation; high strength-to-weight composites; high-temperature superconducting materials for low-drag passive magnetic bearings; Kelvar; Metglass; graphite epoxy.
Unique Test, Production, Inspection Equipment	High-vacuum spin pit for operational testing of flywhell; precisely controlled filament winding machinery for fabrication.
Unique Software	Algorithms and related software for analyzing and predicting flywheel stresses and system dynamics.
Major Commercial Applications	Uninterruptible power supplies (UPSs); utility-level energy storage; low-Earth orbit (LEO) satellites.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

Flywheels store energy in a rotating mass. The energy density of flywheels is higher than that of batteries or capacitors. For this reason, flywheels are of interest to HPM weapon systems. As with all moving mechanical systems, friction and aerodynamic losses are important. Recent advances in high-temperature superconductivity may produce a frictionless flywheel that can store lots of energy and experience only minimal frictional loss of energy. Being able to operate flywheels in near vacuum will reduce aerodynamic losses.

DATA SHEET 6.6. PULSED INDUCTORS

Developing Critical Technology Parameter	In addition to the electrical requirement of having no more than a few microhenries, these pulsed inductors must also have substantially more mechanical strength than inductors that operate in the average power mode. This additional requirement arises because the currents (which are on the order of thousands of amperes) and, hence, the mechanical forces are much larger in the pulsed mode than that for average power operation.
Critical Materials	Materials that can handle the large currents in the pulsed mode; materials that have combined electrical insulating strength and mechanical insulating strength.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Power utilities; automotive applications.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

The development of pulsed inductors has been of interest in many areas of pulsed power, including nuclear weapons effects simulation. While many of the techniques employed for HPM have been available for some time, there is always a need for innovations that can handle large powers with fast risetimes.

DATA SHEET 6.6. LITHIUM POLYMER BATTERIES

Developing Critical Technology Parameter	Lithium polymer battery technology is a solid-state technology based on ion conductivity in polymers. For pulsed operation relevant to HPM weaponization, the critical capabilities for this technology are an energy density of 300–400 W-hrs/kg, a power density of 4,000 W/kg, and a life cycle of 2,000 cycles.
Critical Materials	High-conductivity polymer electrolytes and gels; high-energy density anodes and cathodes; gelionic materials; conductive elastomers; complex organo-lithium salts; carbon powders; carbon platelets and fibers; polymers with high voltage breakdown strength.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Numerous portable electronic devices (e.g., computers, cell phones, and so forth).
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

Lithium polymer batteries are about 50-percent lighter than other batteries that have the similar capabilities. They are also more rugged—less susceptible to damage caused by mechanical stress and shock.

DATA SHEET 6.6. SUPERCONDUCTORS

Developing Critical Technology Parameter	Superconducting materials that operate above the temperature of liquid nitrogen (77 K).
Critical Materials	Superconducting materials that operate above the temperature of liquid nitrogen (77 K).
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Utilities (reduce energy losses in transmission system); coils and magnets for motors and generators.
Affordability	Will improve significantly when superconductors operate at higher temperatures.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

For application to HPM weapons systems, we are most likely concerned with high-temperature superconductivity. In contrast to copper wires, high-temperature superconductive (HTS) wires allow large currents to pass with minimal ohmic losses. The ability to handle large currents and fast risetimes is paramount. In addition, inductors made of HTS wires can store large amounts of energy. Recent advances in the fabrication of HTS wires will increase the availability, reduce the cost, and create greater flexibility in the engineering of systems using high-temperature superconductivity.

DATA SHEET 6.6. INVERTERS

Developing Critical Technology Parameter	Ability to operate at 5–10 kV in the gigahertz regime for UWB applications. This requires high-density switching elements (e.g., semiconductor switches) that minimize energy losses in the high megahertz to gigahertz regime.
Critical Materials	Semiconductors used in switching; dielectrics for use in capacitors; SiC wide bandgap materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Utilities; air conditioning; automotive.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

Inverters convert DC into AC, which is the essential power source for microwave generation. Inverters are used for changing low-voltage levels from sources such as batteries to the high voltages essential for NB and WB HPM systems. Switching in the power converter circuit is the major source of power dissipation. Switching losses increase with an increase in the frequency of switching. To mitigate this effect, soft switching is used. This concept is based on the principle that energy losses will be minimized if switching occurs when either the voltage or the current is zero at the time of switching. Implementing soft switching in PFNs will increase the net efficiency and improve the lifetime of HPM weapon systems.

DATA SHEET 6.6. PULSED TRANSFORMERS

Developing Critical Technology Parameter	Improve the voltage ratio with a low number of turns in the transformer. Any reduction that is consistent with signal fidelity is an improvement.
Critical Materials	Core materials that have minimum dispersion.
Unique Test, Production, Inspection Equipment	Test equipment that can measure pulse shapes in the nanosecond range.
Unique Software	NC machining software.
Major Commercial Applications	Air pollution control; water purification; process control systems.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

PFNs are the glue that makes HPM NB and WB systems work. The PFNs take the prime source of energy and transform it into the desired radiated waveform. An extensive variety of PFNs are available, and each is tailored to a unique waveform. The differences between PFNs reside in the way the various components are coupled to one another. The PFN components, in addition to generating innovative systems integration ideas and using engineering know-how, provide the options for peak and average power and waveform design. PFNs may consist of various combinations of switches, capacitors, flywheels, spark gaps, pulsed inductors, inverters, and pulsed transformers. Depending on the application, superconductivity may also play an important role in PFN design.

Pulse transformers are used in PFNs when high voltage and efficiencies are required. They are used in conjunction with other components in the PFN to provide the desired voltage to the load.

DATA SHEET 6.6. NARROW-BAND (NB) ANTENNAS

Developing Critical Technology Parameter	Antenna designs that can produce an antenna gain greater than 20 dB (narrow beam), can operate at high feed-point voltages without causing air breakdown, and can produce a peak effective radiated power level of 100 MW or more or an average effective radiated power level of 1 MW or more.
Critical Materials	Materials suitable for an antenna structure that can operate continuously in the Mega-volt regime with electric field levels in the tens of Megavolts per meter and higher, without succumbing to air breakdown. Other materials include polyethylene, polypropylene, transformer oil, SF_6.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Theoretical models and related validated computer codes that can evaluate NB antenna designs to improve the effective radiated power.
Major Commercial Applications	Commercial radar; communication antennas.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

NB microwave antennas are, for the most part, extensions of conventional microwave antennas. The major distinction is that they operate at substantially higher powers and shorter pulse duration than conventional antennas. Figure 6.6-23 is a schematic for an HPM antenna system.

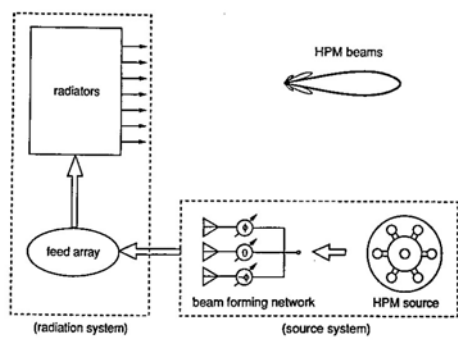


Figure 6.6-23. Schematic of an HPM Antenna System
(Source: Y. Rahmat-Samii, D.W. Duan, and D.V. Giri, 1992)

Various types of HPM NB antennas have been used. The most common antenna has been the rectangular horn. In addition to this conventional antenna, more sophisticated shapes based on reflector geometry have been proposed. These include, for example, an offset shaped single-reflector antenna fed by a generally configured array feed (see Figure 6.6-24).

Common to all HPM antennas is the capability to operate in large electric fields. All antennas contain metallic elements, and these elements reduce the air breakdown limits below the theoretical limits in free space. For example, Figure 6.6-25 shows a reduction of the breakdown field when an aperture is present. This figure applies for the particular frequency of 3 GHz, but the general result that apertures reduce the breakdown field applies at all frequencies. Figure 6.6-26 shows microwave breakdown of ambient air at various altitudes, frequencies, and pulse durations. As observed, the breakdown limits improve with increasing frequency.

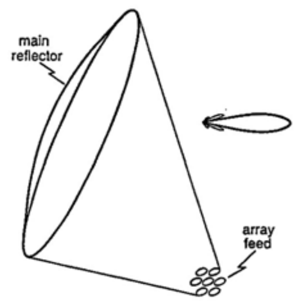


Figure 6.6-24. HPM Reflector Antenna Geometry: An Offset Shaped Single-Reflector Antenna Fed by a Generally Configured Array Feed (Source: Y. Rahmat-Samii, D.W. Duan, and D.V. Giri, 1992)

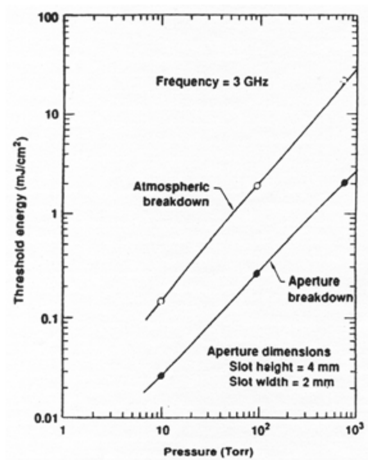


Figure 6.6-25. Reduction of the Air Breakdown Threshold Energy When an Aperture is Present (Source: Benford and Swegle, 1992)

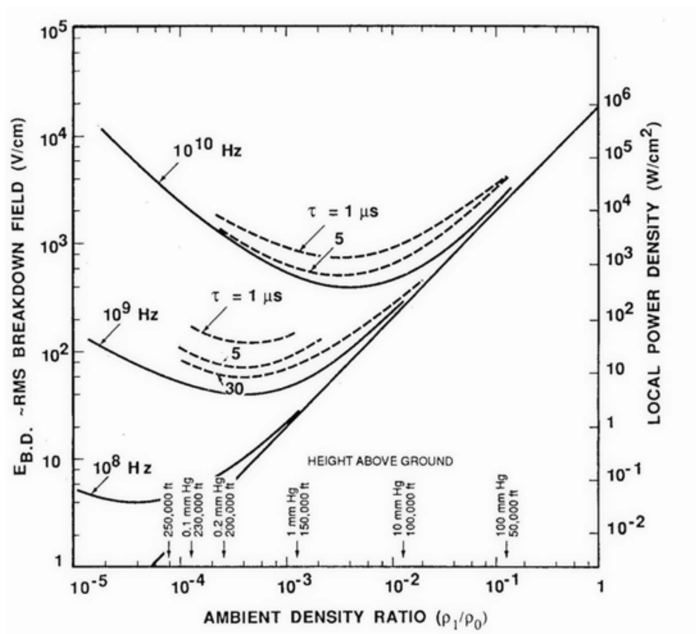


Figure 6.6-26. Microwave Breakdown of Ambient Air at Various Altitudes, Frequencies, and Pulse Durations (Source: Benford and Swegle, 1992)

REFERENCES

Benford, J.N., and J. Swegle, *High Power Microwaves,* Artech House, Inc., Canton, Massachusetts, 1992.

Rahmat-Samii, Y., D.W. Duan, and D.V. Giri, “Canonical Examples of Reflector Antennas for High-Power Microwave Applications,” *IEEE Trans. Electromagn. Compat.*, Vol. EMC–34, No. 3, pp. 197–205, August 1992.

Taylor, C.D., and D.V. Giri, *High-Power Microwave Systems and Effects*, Taylor and Francis, Washington, D.C., 1994.

DATA SHEET 6.6. WIDE-BAND (WB) ANTENNAS

Developing Critical Technology Parameter	Antenna designs that reduce temporal and spatial frequency dispersion so that the radiated pulse has risetime in the 0.1- to 1.0-ns range, a full width at half maximum (FWHM) less than 0.30 ns, and range-field product greater than 200 kV.
Critical Materials	Polyethylene; polypropylene; transformer oil; SF_6; other equivalent materials that can operate at high altitudes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Conventional radar; impulse radar.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The duration of a single impulse-like waveform in a WB system nominally ranges from 0.1 to several nanoseconds. In some cases, a single pulse or other type of WB waveform has a longer duration. The frequency spectrum for this individual pulse is nearly constant over a frequency range extending into the hundreds-of-megahertz or gigahertz region.

A narrow frequency band where EM energy is readily absorbed is called a resonance region or simply a resonance. If the characteristic dimensions of a target are large (e.g., aircraft, tank) compared with the "attacking" wavelength, an abundance of resonances are usually present. The target (seen as a resonant cavity) will often be overmoded. This is nearly always the case of interest. If the energy of a WB pulse is large enough, it could conceivably couple into a target in many different places and simultaneously disrupt several internal electronic systems. The pulse repetition frequency can also play an important role in disrupting a system.

The antenna choice plays a critical role in the lethality of a WB weapon. While traditional antenna designs (e.g., the horn antenna and the biconical antenna) may be satisfactory, Dr. Carl Baum, in 1991, developed a new kind of antenna based specifically on the idea of radiating impulse-like transient fields. This type of antenna was coined an impulse radiating antenna or IRA (see Figure 6.6-27). It is capable of generating a very narrow pulse plane wave at a large distance and concentrating the energy in a narrow beam. IRA-type antennas have been under development by Farr Research over the last decade.

REFERENCES

Baum, C.E., E.G. Farr, and D.V. Giri, "Review of Impulse-Radiating Antenna," W. Ross Stone (Ed.), *Review of Radio Science, 1996–1999*, Oxford University Press, 1999.

Prather, W.D., C.E. Baum, F.J. Agee, J.P. O'Laughlin, D.W. Scholfield, J.W. Burger, J. Hull, J.S.H. Schoenberg, and R. Copeland, "Ultra Wideband Sources and Antennas," in *Ultra Wideband/Short Pulse Electromagnetics 4*, E. Heyman and J. Shiloh (Eds.), Plenum Press, 1998.

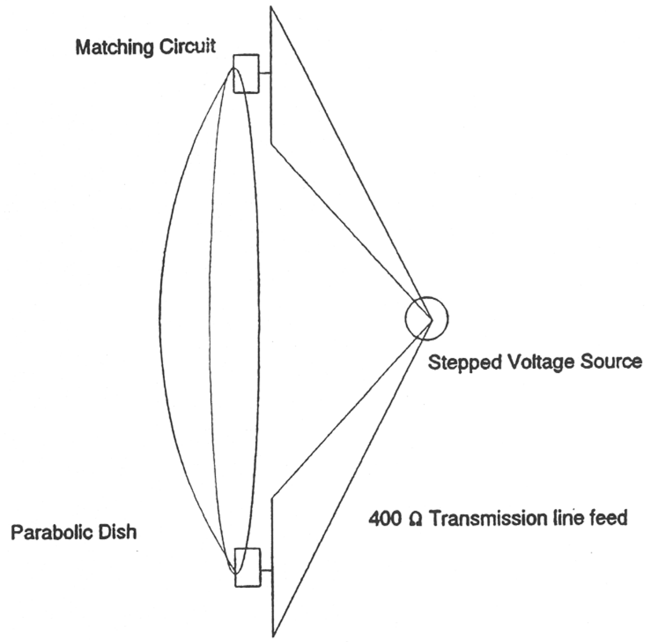


Figure 6.6-27. Impulse Radiating Antenna (IRA) (Source: Farr, 1992)

DATA SHEET 6.6. ANTENNA VOLTAGE INCREASE

Developing Critical Technology Parameter	Antenna feed-point geometry and related materials that can operate in the hundreds-of-kilovolt to Megavolt regime, with peak electric field levels equal to or exceeding the nominal air breakdown field of 24 MV/m at atmospheric pressure and for pulses in the subnanosecond regime.
Critical Materials	Materials that can function without degradation over thousands of pulses in the Mega-volt regime, with electric field levels in the tens of Megavolt-per-meter and higher regime and for pulses in the subnanosecond regime in normal atmospheric conditions without succumbing to air breakdown. Other materials include polyethylene, polypropylene, transformer oil, and SF_6.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Theoretical models and related validated computer codes that can evaluate WB antenna feed-point designs for mitigating voltage breakdown conditions.
Major Commercial Applications	Commercial radar; communication antennas.
Affordability	Required research levels not yet identified.

BACKGROUND

Peaking switches are capable of generating voltages in the hundreds-of kilovolt to tens-of-Megavolt range. When these voltages reach the feed-point of the antenna, air breakdown can occur. When air breakdown occurs, an ionized cloud is produced in the antenna's near field. This leads to a dramatic change in the load impedance of the antenna, as seen by the transmission line connecting the antenna to the peaking switch. This results in reflection of the pulse back to the peaking switch and a dramatic reduction in gain. In the absence of material boundaries, the breakdown field in air at standard atmospheric conditions is 24 kV/cm. This breakdown field level is reduced in the presence of material boundaries but can also be increased as the pulse duration is reduced. This latter effect occurs at small pulse duration when there is insufficient time for the breakdown process to be maintained.

Figure 6.6-28 shows the general trend of increasing the breakdown field by decreasing pulse duration down to 1 μs. Although not shown in this figure, the trend of increasing the breakdown field by decreasing pulse duration continues into the subnanosecond pulse range. This figure also shows the increase in the breakdown field strength with the increase in frequency (appropriate for CW applications).

REFERENCES

Benford, J.N. and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

Prather, W.D., F.J. Agee, C.E. Baum, J.M. Lehr, J.P. O'Laughlin, J.W. Burger, J.S.H. Schoenberg, D.W. Scholfield, R.J. Torres, J.P. Hull, and J.A. Gaudet, "Ultra Wideband Sources and Antennas," in *Ultra Wideband/Short Pulse Electromagnetics 4*, E. Heyman et al. (Eds.), Plenum Press, 1988.

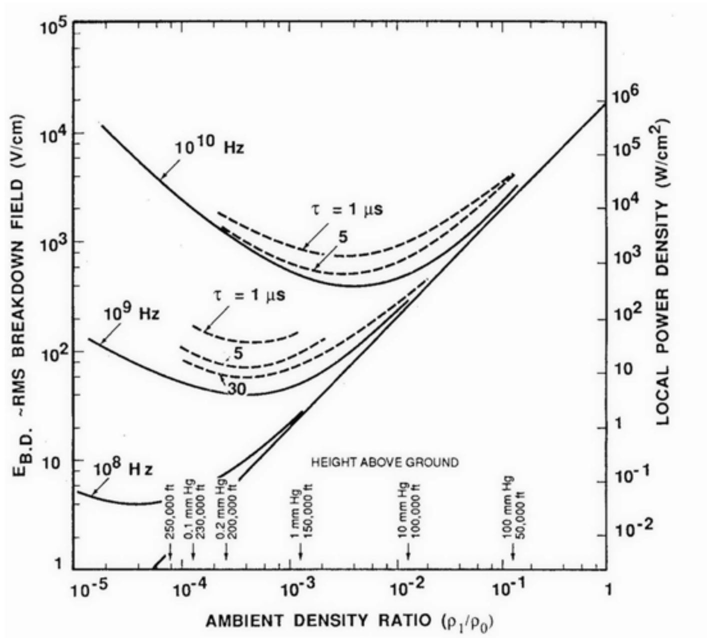


Figure 6.6-28. Microwave Breakdown of Ambient Air at Various Altitudes, Frequencies, and Pulse Durations (Source: Benford and Swegle, 1992)

DATA SHEET 6.6. INSULATION FOR WIDE-BAND (WB) SOURCES

Developing Critical Technology Parameter	For traditional insulation functions, (i.e., those that provide sufficient standoff voltage), the critical technical parameters are as follows: they must have very low frequency dispersion and a low-loss tangent between 100 MHz and 10 GHz to ensure the integrity of the subnanosecond risetime pulse. For example, Rexolite 1422 has a dielectric constant of about 2.5, with a loss tangent of 0.00047 and a relative change of less than 0.005 in this frequency range. To operate in high-pressure hydrogen enclosures without flow or creep, great mechanical strength is required (e.g., Rexolite has a tensile strength of about 7,000 psi). Being resistant to hydrogen would also improve insulating capabilities. For use in an EM lens, the robust structural properties of high tensile strength, minimal flow, and creep are not required. Neither is the requirement to be resistant to hydrogen. Materials that are essentially dispersion free and have low-loss tangent and about the same dielectric constant as transformer oil are required.
Critical Materials	For traditional insulation functions (i.e., provide sufficient standoff voltage), the critical materials are polycarbonate resins (e.g., Lexan^{TM}), Rexolite 1422, Torlon, G-10, and Kel-f. For EM lens applications, the critical materials are polypropylene and polyethylene. Artificial dielectric materials that meet either the standoff voltage or lens requirements are desired.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial radar; high-power communication antennas.
Affordability	Required research levels not yet identified.

BACKGROUND

Insulators for WB systems are required not only to provide the required standoff voltage (a traditional insulator role), but also to retain the shape of the subnanosecond risetime of the pulse. At the frequency range of interest (roughly the reciprocal of the risetime), insulators for WB application must have minimal dispersion and loss.

The development of materials that can meet all the requirements for the standoff voltage application is a major technical challenge. In addition to being able to provide sufficient standoff voltage, the dielectric materials must have very low frequency dispersion and a low-loss tangent between 100 MHz and 10 GHz. These latter EM requirements will ensure that the temporal shape of the subnanosecond risetime pulse generated by the source will be intact. To operate in high-pressure hydrogen enclosures without flow or creep, the dielectric materials must have great mechanical strength. Being resistant to hydrogen would also improve insulating capabilities and extend the lifetime.

For use in an EM lens, the robust structural properties of high tensile strength, minimal flow, and creep and the requirement to be resistant to hydrogen are not required. Materials that are essentially dispersion free and have low-loss tangent and about the same dielectric constant as transformer oil are required. When this is accomplished, the oil/lens interface will be essentially transparent, thereby minimizing distortion of the wavefront.

REFERENCES

Agee, F.J., C.E. Baum, W.D. Prather, J.M. Lehr, J.P. O'Laughlin, J.W. Burger, J.S.H. Schoenberg, D.W. Scholfield, R.J. Torres, J.P. Hull, and J.A. Gaudet, "Ultra-Wideband Transmitter Research," *IEEE Trans Plasma Science*, Vol. 26, No. 3, June 1998.

Prather, W.D., F.J. Agee, C.E. Baum, J.M. Lehr, J.P. O'Laughlin, J.W. Burger, J.S.H. Schoenberg, D.W. Scholfield, R.J. Torres, J.P. Hull, J.A. Gaudet, "Ultra Wideband Sources and Antennas," in *Ultra Wideband/Short Pulse Electromagnetics 4*, E. Heyman et al. (Eds.), Plenum Press, 1988.

DATA SHEET 6.6. PHASED ARRAYS

Developing Critical Technology Parameter	This technology applies to NB sources. The critical technologies are the ability to phase-lock sources at high power levels and the development of high-power phase shifters. Any level above current levels are of interest. Phased-array antennas are used to steer the beam rapidly and keep it on target. The speed with which power must be supplied to each element of the array depends on the velocity of the object that is being tracked and illuminated and the velocity of the platform. A common denominator for each scenario is based on the continuous on-target requirements. The radiating antenna should be capable of generating either of the following characteristics: a peak effective radiated power level of 100 MW or more, a single pulse of effective radiated energy of 10 J or more, or an average effective radiated power level of 1 MW or more.
Critical Materials	Polyethylene; polypropylene; transformer oil; SF_6; other dielectrics that can be used for high-power phase shifters.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and related computer codes that integrate acquisition, tracking, and illumination of targets with HPMs.
Major Commercial Applications	Phased-array radar.
Affordability	Appears expensive; required research levels not yet identified.

BACKGROUND

Antennas for NB systems are conceptually similar to those used in conventional radar. At the relatively low power levels used in conventional radar, electronic steering for HPM/RF antennas is possible. This improves the capability of the antenna first to acquire the target and then remain on target. Electronic steering at high power levels remains to be developed. The critical factors are dynamic phase shifting or delay line technology for evacuated wave runs. Figure 6.6-29 shows a schematic of a phased-array antenna.

REFERENCES

Benford, J.N., and J. Swegle, *High Power Microwaves*, Artech House, Inc., Canton, Massachusetts, 1992.

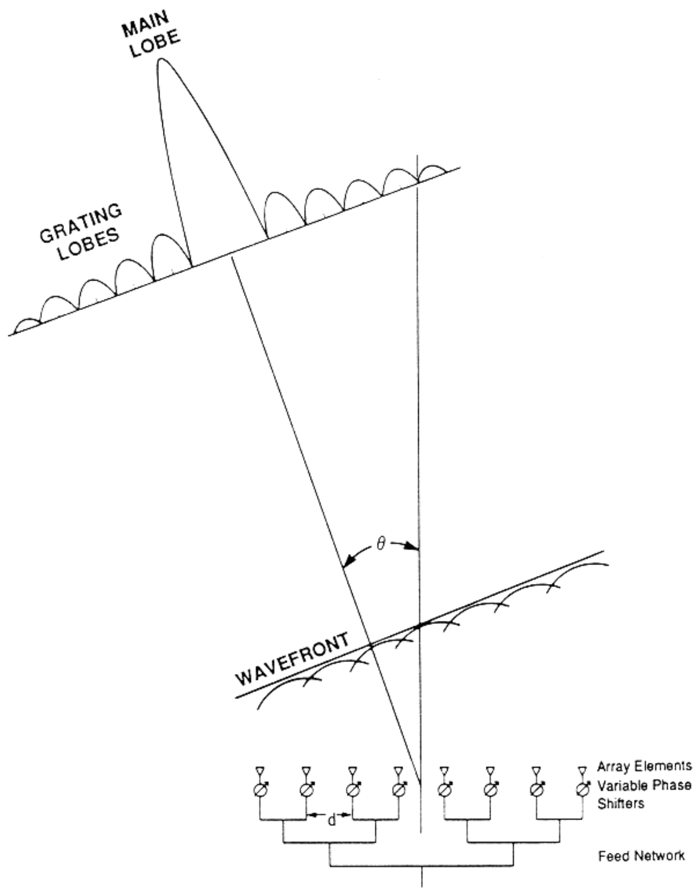


Figure 6.6-29. Schematic of a Phased-Array Antenna (Source: Benford and Swegle, 1992)

DATA SHEET 6.6. ELECTROMAGNETIC (EM) LENS

Developing Critical Technology Parameter	The two general goals of an EM lens are those for an exact lens and those for an approximate lens. For an exact lens, the critical technology parameters are stringent. The lens must be nondispersive in the frequency range of interest, capable of supporting the TEM mode, and capable of redirecting the TEM wave. These conditions require an exact impedance match along the propagation path. For the approximate lens, the requirements are less demanding. The correct phase front must be achieved, but it is not necessary to match the impedance. These considerations apply for a graded dielectric constant with relative dielectric constants between 2 and 6. EM lenses become especially important for pulse risetimes less than 250 ps.
Critical Materials	Polyethylene; polypropylene; transformer oil.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Impulse radar; earth-penetrating radar.
Affordability	Required research levels not yet identified.

BACKGROUND

As pulse risetimes for WB systems become smaller (e.g., less than 250 ps), including optics in the propagation of waves in the transmission line theory for pulsers and antennas is necessary. When the theory of optics, as developed by Baum and Stone, is used correctly in graded dielectric materials, an EM wave can be made to radiate from the source to the exterior volume without dispersion. That is, the pulse shape developed at the source is retained all the way to the target.

Baum and Stone have developed the modern theory of propagation of EM waves in graded dielectric materials, especially as applied to lenses, within the last decade. Figure 6.6-30 shows an experimentally validated application of the lens synthesis theory for a graded dielectric. This configuration enables the wave to be bent around 90 deg without distortion. The theory has been used to develop a lens at the apex of an antenna to correct astigmatism caused by a finite size gas switch. In another application, the theory has been used to develop a focusing lens that was used at the output of a TEM horn. This is shown in Figure 6.6-31. When used in this case, the lens corrected the nonplanarity of the wavefront emerging from the horn. The lens reduced the antenna's inherent dispersion.

REFERENCES

Agee, F.J., C.E. Baum, W.D. Prather, J.M. Lehr, J.P. O'Laughlin, J.W. Burger, J.S.H. Schoenberg, D.W. Scholfield, R.J. Torres, J.P. Hull, and J.A. Gaudet, "Ultra-Wideband Transmitter Research," *IEEE Trans Plasma Science*, Vol. 26, No. 3, June 1998.

Baum, C.E., and A.P. Stone, "Synthesis of Inhomogeneous Dielectric Dispersionless TEM Lenses for High-Power Application," *Elecromagnetics*, Vol. 20, 2000.

Baum, C.E., and A.P. Stone, *Transient Lens Synthesis*, Hemisphere Publishing Corporation, Washington, 1991.

Baum, C.E., and A.P. Stone, "Unipolarized Generalized Inhomogeneous TEM Plane Waves in Differential Geometry Lens Synthesis," *Sensor and Simulation Note 433*, Air Force Weapons Laboratory, January 1999.

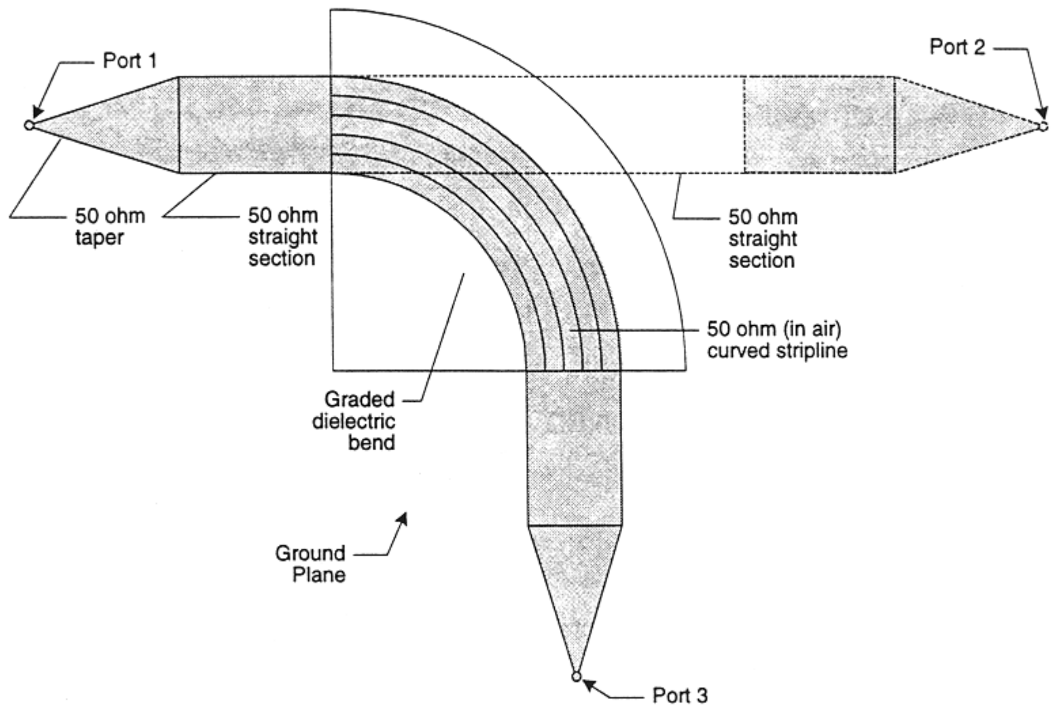


Figure 6.6-30. Strip Line Test Fixture (Source: Bigelow and Farr, 1998)

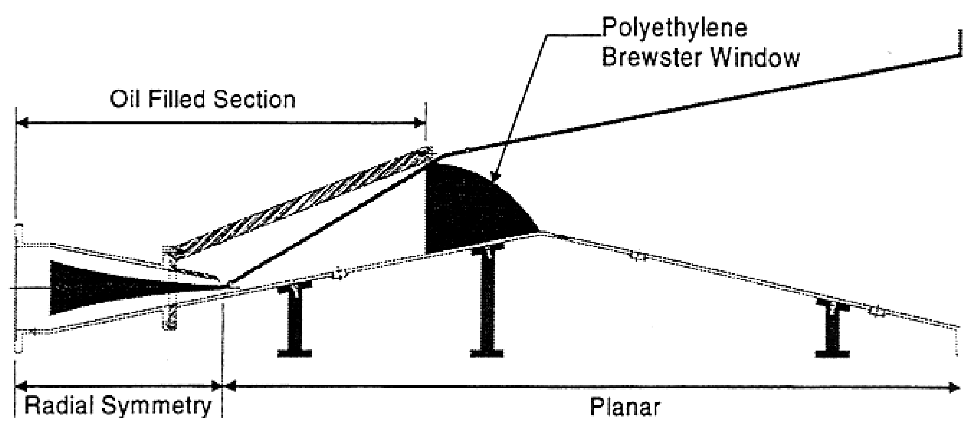


Figure 6.6-31. Diagram of a TEM With a Brewster Angle Window Lens (Source: Agee et al., 1998)

DATA SHEET 6.6. EXPLOSIVE MAGNETO-HYDRODYNAMIC GENERATORS (EMHDGs)

Developing Critical Technology Parameter	Several critical parameters are relevant to the development of these generators for HPM weapons systems. The first is to improve the energy efficiency to greater than 12 percent. The second is to increase the radial voltage above 20 kV. For a firing rate of 1 pps, an energy per pulse greater than 100 MJ is desired. For 1–100 pps, an energy per pulse between 1 and 10 MJ is desired. For 100–1,000 pps, an energy greater than 1 kJ is desired
Critical Materials	High-temperature materials that can operate in the desired pps range during the explosive phase.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	This technology appears to be connected to other military applications, principally railguns. There does not appear to be a viable commercial prospect in the foreseeable future.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

EMHDGs convert explosive energy directly into electrical energy in a burst mode. Because the energy density of these devices ranges from 4,500 to 6,000 J/g for common explosives, they can provide useful energy per pulse even at low-energy efficiency.

RF munitions are radically different from conventional NB and WB microwave sources. These single-shot expendable microwave sources derive their energy from explosively driven pulsed power sources. They use explosively driven magnetic flux compressors for current and power amplification.

RF munitions appear *conceptually* to require a lower level of technology when compared with NB and WB sources. The general feeling in the scientific community is that these concepts do not work as well as reported. The major reason for the poor performance is perceived to be the relatively low-frequency generation produced by these explosive devices and their inability to radiate efficiently at microwave frequencies. However, in principle, there is no reason that such systems cannot be designed to radiate effectively.

DATA SHEET 6.6. TOPOLOGY AND SYSTEM MODELS

Developing Critical Technology Parameter	A description of the electrical connectivity and information flow in military systems that include components, buses, transmission lines, and related hardware for mission-critical control functions (vertical stabilizer, missile launch, and so forth) is information that should be rendered in a structured format (i.e., a topology that makes it possible to predict system performance from incident unwanted EM signals such as those caused by HPM/RF). A desired goal is to predict system response to within an order of magnitude of the key parameters of the external electric field: amplitude, risetime, decay time, repetition rate, and pulse duration. The frequency range of interest is 100 MHz to 35 GHz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Mathematical models and related computer codes that describe the electrical connectivity, electronics, and information flow in military systems. These models should include components, buses, transmission lines, and related hardware for determining the time behavior of mission-critical control functions (vertical stabilizer, missile launch, and so forth) under the HPM/RF threat. Essentially, the required software provides a complete simulation of the system under the HPM/RF threat.
Major Commercial Applications	Simulation of commercial aircraft; electric power facilities, transportation systems, and so forth in the presence of unwanted EM inference.
Affordability	This is affordable today when the interior EM fields can be computed.

BACKGROUND

In defending electronic and communication systems against unwanted EM signals caused by HPM/RF, a major consideration is predicting how these unwanted EM signals, which penetrate to the interior volume of the system, adversely affect system performance. The interior volume is the region that hosts the electronics, computers, and local area networks (LANs) that form the information systems (e.g., avionics, target acquisition). Higher interior EM field levels are more likely to cause system malfunctions.

By more efficiently organizing and identifying the critical steps and computational procedure, we can reduce the uncertainty of predicting the interior field and the concurrent BER. In addition, we will be able to devise mitigation procedures more efficiently. The result will be to minimize the probability of system malfunction.

The basic assumption for this discussion is that all systems are contained within an enclosure. That is, none of the systems are exposed directly to the incident EM field. This is clearly the most prevalent case. Typical enclosures are buildings, aircraft, ground vehicles, and so forth.

Figure 6.6-32 is a flow diagram for determining the system response. The blocks on the right-hand side of this figure are based on the topology theories developed by Baum, Tesche, and others. These technologies were originally developed to evaluate the survivability of systems against the various EMP threats [e.g., HEMP, source-region electromagnetic pulse (SREMP)]. They are applicable with some modification to the HPM/RF threat. The shaded blocks on the left-hand side of Figure 6.6-32 are those technologies that have received minimal attention in the HPM/RF arena. The reason for this lack of attention is that system-level problems caused by HPM/RF-level EM fields are less obvious than those caused the powerful EMP pulses. These subtle but important system-level problems are just beginning to be recognized. They represent the next level of topology.

The starting point is the EM field from the source. The external field striking the surface of the enclosure is known from the source characteristics. This is a straightforward calculation even when we account for ground scattering between the source and the surface of the system.

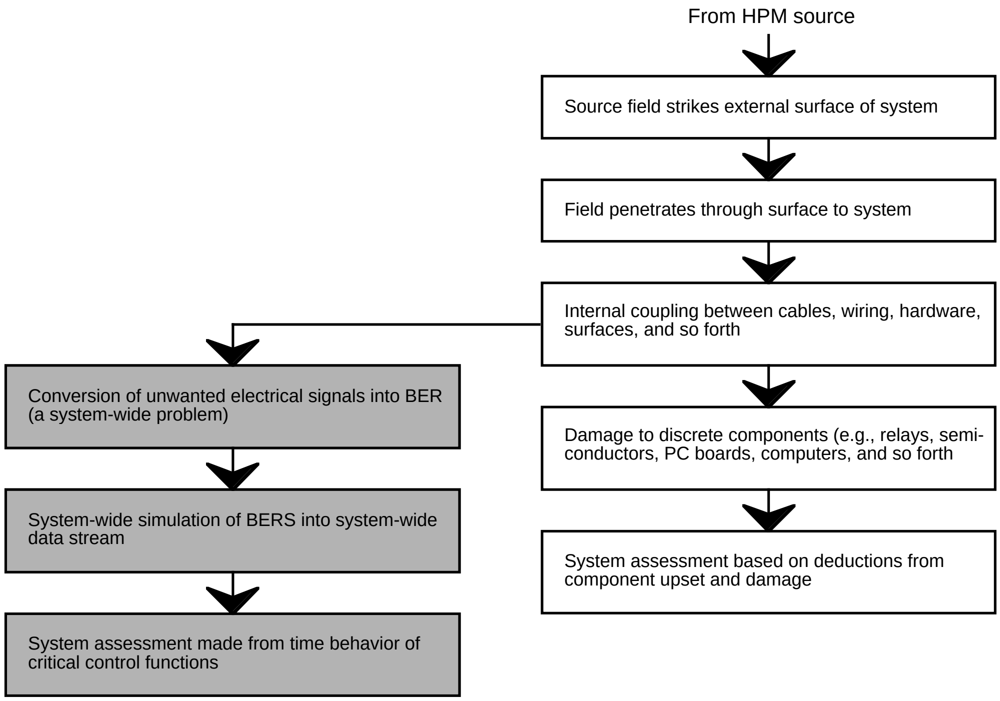


Figure 6.6-32. Topology for Determining System Response

The penetration of the EM waves through the external surface is a complicated and difficult problem when the surface has apertures, seams, sharp corners, and other irregularities. Despite these obstacles, considerable progress has been made in this area because of the need to ensure system survivability against the EMP threats. Hundreds of papers have been written on this topic.

The computation of internal EM coupling between the numerous cables, wires, conducting and dielectric surfaces, and other hardware is major technical challenge. The problem is one of sheer complexity because of the irregular layout of components required by the interior geometry.

In certain relatively simple cases (e.g., a few objects in room), accurate prediction of the internal EM field is possible. However, as the number of objects in the room increases, the computational burden becomes virtually unmanageable with today's technology. Moreover, small changes in the locations of interior equipment can cause large changes in fields—sometimes in critical places where they cause bit errors.

If we know the internal EM field, we can compute the vulnerability of selected components. There may be as much as 30 dB of uncertainty in predicting the internal EM field at critical points. Hence, prediction of system upset is often highly uncertain. Alternative approaches are desired.

REFERENCES

Baum, C.E., "Electromagnetic Topology for the Analysis and Design of Complex Electromagnetic Systems," in I.E. Thompson, L.H. Luessem, Martinus Nijhoff, and Dordrecht (Eds.), *Fast Electrical and Optical Measurements,* Volume I, pp. 467–547, 1986.

Lee, K.S.H. (Ed.), *EMP Interaction: Principles, Techniques and Reference Data,* Hemisphere Publishing Co., New York, 1989.

Tesche, F.M., "Modeling Techniques for EMC Analysis," *Review of Radio Science 1996–1999,* Oxford Science Publications, Oxford University Press, 1999.

Tesche, F.M., M. Ianoz, and T. Karlsson, *EMC Analysis Methods and Computational Models*, John Wiley and Sons, New York, 1997.

DATA SHEET 6.6. LABORATORY SIMULATION OF HIGH-POWER MICROWAVE/RADIO FREQUENCY (HPM/RF) EFFECTS

Developing Critical Technology Parameter	Hardware-in-the-loop (HIL) and supporting computer simulation models that predict the response of military information systems against the HPM/RF threat. Critical technology parameters are the wave shape and peak amplitude of the electric field that strikes the exterior surface of the system. Laboratory simulation should model the entire system and be capable of predicting the threshold of adverse effects to within 10 dB of the field's peak amplitude and within factors of 2–3 of its wave shape parameters: risetime, decay time, repetition rate, and pulse duration.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	A key element in identifying the causes of system malfunction is determining the bit error rate (BER) and message error rate (MER) at key locations in the system. Unobtrusive hardware (i.e., hardware that does not change the local EM field) that can be inserted in systems and measure BERs in real time is required.
Unique Software	Analytical models and related software that model the response of the entire information system in the presence of HPM/RF EM signals.
Major Commercial Applications	Modeling the performance of aircraft in the presence of EMI.
Affordability	Should be readily affordable since laboratory simulation models of this type already exist in the airline industry.

BACKGROUND

Predicting HPM/RF-caused malfunctions in real systems is extremely complicated because nearly all the systems' functions are connected and integrated into a single computer system. The information paths for mission-critical function may share the nodes. Predicting system performance analytically in an accurate manner is virtually impossible.

On the other hand, modeling the performance of the entire system is not especially difficult since the equations would have to be known to construct the network. A computer system's performance is determined by the BERs in the various parts of the system. The connection between the HPM/RF unwanted EM field and system performance is the conversion of the unwanted signal into BERs at critical points in the network. Figure 6.6-33 shows the sequence of events.

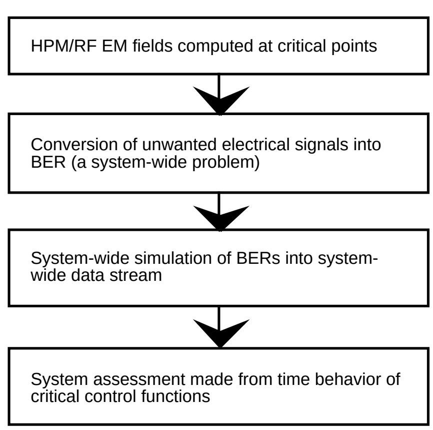


Figure 6.6-33. Elements of Laboratory Simulation for HPM/RF Effects

DATA SHEET 6.6. MINIMIZATION OF NUMBER OF TESTS

Developing Critical Technology Parameter	The cost for testing military systems against the HPM/RF threat is high. This often necessitates conducting only a small number of tests. Yet, the number of possible scenarios between threat and victim system is large and, for many cases, is practically infinite. Despite these circumstances, statistical theories that establish confidence greater than 50 percent are required to assess system susceptibility and/or vulnerability.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Robust statistics theories that improve confidence will improve software reliability.
Affordability	Estimate minimal cost required for incorporating statistics theories for testing; use of these theories could result in large savings in testing time.

BACKGROUND

For more than 20 years, the interest in quantifying the effects of unwanted EM signals (e.g., HPM/RF) on electronic and information systems has been increasing. Significant progress has been made in developing theoretical models that predict the generation of unwanted EM waves through inadvertent apertures and POEs. In contrast, a significant amount of theoretical work still needs to be done to understand and then predict and ultimately mitigate the effects of unwanted signals caused by HPMs.

The response of large, complex electronic systems (e.g., LANs) to these unwanted EM signals can range from temporary upset to long-term upset to permanent damage of individual components [e.g., personal computers (PCs)] and subsystems composed of PCs and other electronic hardware. Frequently, the important issue is not what happens to an individual component but what happens to mission-critical functions: sets of electronic components. Efficient statistical methods for predicting system response have to be developed by reducing greatly the number of tests required to determine the probability of failure of mission-critical functions.

HPM effects on systems are both subtle and random. The problem is complicated further because the commercial and military systems for which HPM effects are a concern are essentially large telecommunication and/or computer networks whose behavior depends on the random interaction of discrete electrical messages, such as control functions (e.g., "turn the heat on"). Systems of this type are called *discrete event dynamic systems* (DEDSs). The study of these systems is itself an emerging technology. DEDSs are essentially man-made systems and, in this sense, are different from the *continuous variable dynamic systems* (CVDSs) that are modeled for physical systems.

As shown in Ho (1992), the response of DEDSs depends on the initial state of the system (i.e., DEDSs are not autonomous systems). Under these conditions, the number of initial states is essentially infinite since each state can be viewed as a unique configuration of all the transistors in the system. Contemporary military information systems contain literally hundreds of millions of transistors. Thus, even in a case where the scenario between the HPM/RF source and the victim is fixed, a randomness exists in the problem because of the uncertainty of the system's initial state. Determining the minimum number of tests required for a prescribed confidence has been addressed for this case using nonparametric statistics (Kohlberg and Gardner). Further work is required to infer system performance from a limited number of experiments.

REFERENCES

Ho, Yu-Chi, (Ed.), *Discrete Event Dynamic Systems*, IEEE Press, Piscataway, NJ, 1992, 1989.

Kohlberg, I., and R. Gardner, *Interpreting Electronic System Response to Unwanted Electromagnetic Signals Using Non-Parametric Statistics,* presented at the International Symposium on Electromagnetic Compatibility, October 5–7, 1999, Magdeburg, Germany.

DATA SHEET 6.6. FAULT-TOLERANT CIRCUITS AND TECHNIQUES

Developing Critical Technology Parameter	Any level of circuit design and techniques that include the ability to reset the system in a timely way.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Reliable software in support of fault-tolerant circuits and techniques.
Major Commercial Applications	Wide variety of EMC and EMI applications.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Fault-tolerant circuits and related software provide a complementary means of mitigating the effects of unwanted EM signals as compared with the brute force method of reducing the EM field by hardening techniques. A key element in this process is to be able to detect the presence of an unwanted EM signal, and being able to detect the presence of an unwanted EM signals requires an intimate knowledge of the flow of information within the LAN.

DATA SHEET 6.6. RADIO FREQUENCY (RF) HARDENING OF APERTURES

Developing Critical Technology Parameter	This is not a revolutionary technology. However, incremental improvements (some innovative) are being made continuously. These improvements are reported in international meetings on EM techniques. Combinations of materials and related aperture designs that increase the attenuation of unwanted signals in the 100-MHz to 35-GHz frequency range by at least 10 dB from current levels
Critical Materials	Materials that absorb microwave energy with minimal reflection in the 100-MHz to 35-GHz frequency range and do not interfere with the normal functioning of the aperture.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Time-domain computer codes that calculate the penetration of EM waves through apertures of various shapes and are comprised of materials with arbitrary conductivity, permeability, and permittivity. These time-domain computer codes should be capable of handling pulses that have tens of picosecond risetimes and wide bandwidths with the upper limit of frequency above 35 GHz.
Major Commercial Applications	Used in wide variety of EMC and EMI applications.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

The theoretical prediction of EM fields that penetrate apertures of various shapes that are conformal with exterior surfaces is well established for canonical shapes (e.g., slits, rectangles, circles, and so forth) and for highly conductive surfaces. The theory is not as well established for complex materials, such as those that might be used in low observable (LO) aircraft and other military platforms, and/or for more irregular shapes. In particular, one may find that the use of such shapes and new materials could minimize the penetration of unwanted signals that enter a system's interior volume.

DATA SHEET 6.6. INCOMPLETE SHIELDS

Developing Critical Technology Parameter	This is not a revolutionary technology. However, incremental improvements (some innovative) are being made continuously. These improvements are reported in international meetings on EM techniques. Any level of enhanced or equivalent shielding effectiveness that uses an incomplete shield instead of a complete shield. The frequency range of interest is 100 MHz to 35 GHz.
Critical Materials	Ferrites; dielectrics; bonding materials.
Unique Test, Production, Inspection Equipment	Automated equipment that measures the electric and magnetic shielding effectiveness of incomplete shields for maintaining hardness.
Unique Software	Computer codes and algorithms to predict shielding effectiveness of incomplete shields.
Major Commercial Applications	Wide variety of EMC and EMI situations where savings in dollars, space, weight, or volume could be achieved using incomplete shields instead of complete shields.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Interior shielding is one way to reduce the coupling between cables and between cables and other surfaces that are capable of conducting current. EM shielding is an established technology. It can often be implemented successfully if there are no restrictions on weight, volume, or other operational constraints. Very often, however, the practicalities of the situation (e.g., cockpit) preclude the implementation of a complete shield. Only portions of cables or conducting surfaces can be shielded. Under these conditions, shielding formulae obtained from handbooks or other established sources may not be correct because they were determined from EM field boundary conditions that are different from the actual case.

Quantifying the effectiveness of an incomplete shield requires the solution of EM boundary value problems for shields that have irregular shapes. These problems may be one of a kind, and the theoretical solution to these unique problems requires the use of sophisticated frequency domain or time-domain EM computer codes.

In addition to the theoretical problems of incomplete shields, we also need to consider methods for maintaining the integrity of these shields during their operational lifetime because portions of the shield may be exposed to environments that have not been experienced previously.

DATA SHEET 6.6. SHIELDING MATERIALS

Developing Critical Technology Parameter	This is not a revolutionary technology. However, incremental improvements (some innovative) are being made continuously. These improvements are reported in international meetings on EM techniques. Any level of enhanced shielding that can be used in place of current levels using materials that meet the required operating requirements. The frequency range of interest is 100 MHz to 35 GHz. The operating requirements could mean reduced volume and/or weight for same shielding effectiveness, greater range of operating temperatures, greater range of operating frequencies, unique effectiveness in a selected frequency band, and so forth.
Critical Materials	Ferrites; composite materials; dielectric materials. Of particular interest are materials that have desirable nonlinear or saturation features in the range of interest.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Wide variety of EMC and EMI situations where savings in dollars, space, weight, or volume could be achieved using improved shielding materials.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

Interior shielding is one way to reduce the coupling between cables and between cables and other surfaces that are capable of conducting current. EM shielding is an established technology. Significant improvements in shielding effectiveness can be obtained by using materials that mitigate the intensity of the EM fields that propagate through them. Materials that have nonlinear behavior because of the frequency dependence of permittivity and permeability are of special interest in selected frequency bands.

DATA SHEET 6.6. FARADAY CAGE

Developing Critical Technology Parameter	This is not a revolutionary technology. However, incremental improvements (some innovative) are being made continuously. These improvements are reported in international meetings on EM techniques. Improve electric and magnetic shielding effectiveness exceeding 30 dB, replace existing faraday cages, and employ materials that meet weight and volume requirements for the system. In the context of HPM/RF, Faraday cages can be employed in a wide range of frequencies. The upper end of the frequency range is about 35 GHz, although it has been suggested that 100 GHz could be a more realistic limit in the next decade. The main range of interest is probably the 100-MHz to 5-GHz range, which includes the L-band and S-band radar bands (a frequently used range of operation for NB HPM sources).
Critical Materials	Ferrites; composites; dielectrics; gaskets; mesh; inductive caulk; paint; RF fingers; bonding materials that can configure stratified layers for shielding purposes. Of particular interest is nanotube technology. These hollow chains of carbon provide good shielding because they are extremely strong and lightweight and are highly conductive.
Unique Test, Production, Inspection Equipment	Equipment that can conduct shielding effectiveness measurements and meet or exceed IEEE standards.
Unique Software	None identified.
Major Commercial Applications	Wide variety of EMC and EMI applications.
Affordability	Too early to determine with reasonable degree of confidence. Highly variable because of wide variation in geometry.

BACKGROUND

A Faraday cage is a large enclosed conductive structure (generally metal or metal mesh) that excludes EM fields from penetrating the interior volume. The interior volume may host entire systems and subsystems. When used in the interior of a building, a Faraday cage is sometimes called a shielded room. The theoretical Faraday cage is a continuous, highly conductive surface that is free of penetrations and seams. When the appropriate shielding materials are used to construct the surface, the Faraday cage becomes an effective first line of defense against penetration by unwanted EM fields.

In practice, however, the theoretical Faraday cage is difficult to implement. Physical penetrations are usually required for system functionality (e.g., bringing in exterior cables and personnel entry). These penetrations produce inadvertent apertures. Methods must be developed to minimize the adverse effects of these inadvertent apertures. If the volume containing the systems and subsystems to be protected is large, the surface area of the Faraday cage will also be large. For many types of mobile platforms, the added weight and volume penalty can be severe; therefore, materials that are highly conductive and lightweight and can be fabricated in different shapes are of great interest.

DATA SHEET 6.6. TRANSIENT SUPPRESSION

Developing Critical Technology Parameter	This is not a revolutionary technology. However, incremental improvements (some innovative) are being made continuously. These improvements are reported in international meetings on EM techniques. Enhanced protection against the transient caused by the HPM/RF signal using combinations of materials, components, and circuit techniques. These elements would include, for example, metal oxide varistors, ferrites, RF filters, and so forth. Insertion of these elements must meet the operating requirements—weight, volume performance, and so forth—for the system being protected. The frequency domain of interest is 100 MHz to 35 GHz. Suppression of transients may involve combinations of reducing peak amplitude of either or both voltage and current, reducing frequency content in certain bands, reducing power transfer, and so forth. The precise level of reduction of these entities is highly system dependent. Under most circumstances, a minimum improvement of 10 dB is desired to warrant implementation of these devices and techniques.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Laboratory-scale pulse voltage and current sources that can be used to test systems and validate hardware implementation.
Unique Software	Transient analyses models and software that can guide and corroborate implementation of transient suppression techniques.
Major Commercial Applications	Wide variety of EMC and EMI applications.
Affordability	Generally inexpensive using existing commercially available hardware.

BACKGROUND

Suppression of unwanted electrical transients in systems has been of interest to the EMC/EMI community since the electronics age began. The techniques relevant to mitigating the effects of HPM/RF on electronic systems are mostly related to hardening these systems against the HEMP threat. The reason for this approach lies primarily in the similarity of pulse shape and frequency content. Although the HPM/RF-generated fields within a electronic system may not be as high as those generated by HEMP, they are large enough to require, for example, clamping of the voltage in both directions—something accomplished by a metal oxide varistor.

For the most part, one can consider transient suppression a mature technology, although methods for improving this capability are always being developed.

DATA SHEET 6.6. GROUNDING SYSTEMS

Developing Critical Technology Parameter	This is not a revolutionary technology. However, incremental improvements (some innovative) are being made continuously. These improvements are reported in international meetings on EM techniques. Any level of enhanced grounding systems that can be achieved in place of current levels employing materials, weight, and volume requirements that meet the operating requirements for the system. The frequency domain of interest is 100 MHz to 35 GHz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Computer codes that model complex grounding systems.
Major Commercial Applications	Wide variety of EMC and EMI applications.
Affordability	Too early to determine with reasonable degree of confidence.

BACKGROUND

An electrical ground is a surface that is maintained at the same potential, usually taken as 0 volts. For a surface to have the same potential, it must have extremely low resistance between any two points on the surface. Effective grounding systems can reduce the propagation and coupling of unwanted EM signals. In addition, they provide a personal safety margin.

Although grounding is an established technology, it has to be improved at the higher frequencies that are characteristic of HPM/RF signals.

REFERENCES

Kodali, V.P., *Engineering Electromagnetic Compatibility*, IEEE Press, Piscataway, NJ, 1996.